

Article

Analytical Hierarchical Process to Establish the Criteria for Choosing Explosives Suppliers in Small and Medium Mining Companies

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Abstract: Mining plays a pivotal role in economies worldwide, contributing to employment, infrastructure, and the supply of essential raw materials. Chile's global mining powerhouse, particularly in copper production, exemplifies this industry's economic significance. The supplier selection process in the mining industry, a complex and multifaceted task, is explored in detail, specifically focusing on explosives procurement, a critical component for mineral extraction. The paper underscores the importance of informed supplier selection decisions, especially for SMEs, which often need more resources and capabilities for efficient management. To address these challenges, the study proposes applying the Analytic Hierarchical Process (AHP), a multi-criteria decision-making methodology, to identify and prioritize the criteria and sub-criteria pertinent to choosing explosives suppliers. A case study in the Coquimbo Region, Chile, involving SMEs in the mining sector is the empirical foundation for this research. Our research highlights that the foremost criterion for SMEs in the Coquimbo Region's mining sector is "relationship with the environment and communities". This reflects the national context of mining community tensions and the rising environmental standards and social expectations, which can profoundly impact mining operations. "Quality of products and services" is the second most crucial criterion, underscoring SMEs' drive to enhance productivity and efficiency. "Contractual compliance" follows closely, signifying the integration of SMEs into broader social and environmental sustainability efforts. Conversely, "innovation" ranks as the least relevant criterion, indicating that SMEs prioritize traditional processes due to limited resources and cost constraints. These insights are valuable for mining supplier company managers, emphasizing the need for sustainability, corporate social responsibility, and management control systems.

Keywords: decision-making; analytical hierarchical process; expert choice; suppliers; sustainability



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1. Introduction

Mining has been a key player in employment, infrastructure, and supplying essential raw materials for society [1,2]. It is becoming an important source of economic development in various world economies [3]. Despite being risky, evidence shows that mining can contribute to a country's economic growth and poverty reduction [4].

Globally, Chile is recognized as one of the largest producers and exporters of minerals, mainly copper. In 2022, Chile's production reached 5.3 million metric tons, equivalent to 28.4% of global copper production [5]. It is responsible for the direct generation of 14.6% of the gross domestic product, although its powerful multiplier effect also contributes to the consumption of goods and services in other industries [6].

It is correct to say that mining, in general, is made up of three large groups: The first is made up of extensive mining, in which the National Copper Corporation of Chile, better known as Codelco, stands out, being a Chilean state-owned company dedicated to copper mining, an area in which it is one of the largest companies in the world. The second group

comprises medium-sized mining companies, primarily national companies belonging to family groups, and, last but not least, the third group includes small mining, which is made up of micro companies and artisanal entrepreneurs [7]. Mining activities are among the primary controversial industries and are a concern worldwide, especially in developing countries such as Chile [8]. Not having the materials and equipment for production can generate significant losses for mining companies [9]. This highlights the importance for mining SMEs to have information to select suitable suppliers.

The selection of a supplier is a complex decision-making process that involves evaluating different suppliers based on qualitative and quantitative criteria, which can often conflict with each other [10]. It is essential to stop and analyze how companies in the mining sector select supplier companies that they deem to be the most suitable for the job and capable of meeting the stipulated requirements [11]. Using explosives in mining is essential and helps facilitate the advancement and extraction of minerals. Not knowing which explosives to use could cause bad results and lead to high operational costs. Therefore, it is vital to recognize the characteristics of the types of explosives, such as detonation speed, density, detonation pressure, etc. [12]. When an explosive is confined inside an auger and detonates, a detonation wave propagates through the surrounding rock. At a point close to the borehole, that detonation wave produces a compression effect as it reaches the borehole, but as it passes the borehole, that stress becomes a tensile stress. This first shock wave travels through the surrounding rock at velocities of between 3000 and 5000 m/s. [13]. The uncertainty of knowing by which criteria to be governed and which decisions are the most accurate can significantly impact the project's development. The supply of explosives is one of the critical processes within the mining value chain [9,14].

When deciding, external and internal factors will directly influence the decision [15]. External factors depend not on the decision-maker but rather on factors such as environment, risk, pressures, time, etc. In contrast, internal factors are related to the person, such as attitude, skills, personal experiences, creativity, and others [11].

Multi-criteria decision-making methods (MCDM) have become necessary in all contemporary engineering practices [16]. That is why we propose employing the Analytical Hierarchical Process (AHP), which is designed to cope with rationality and intuition, to select the best alternative from a series of alternatives evaluated concerning several criteria [17]. This tool helps decision-makers obtain essential results, and its simplicity and power have been evidenced in different applications. The AHP structures a decision problem in a hierarchy that reflects the relationships between the general objective, criteria, and sub-criteria [18]. Once the hierarchical model is built, comparisons are made between pairs of elements, constructing matrices from these comparisons and using aspects of matrix algebra to establish priorities among the details of the next level up [19]. In the last 30 years, the Analytical Hierarchical Process has been used in various areas worldwide [20]. The method has been used in areas as diverse as society, science, education, economics, transportation, location and resource allocation, marketing, production, environmental applications, urban planning, the public sector, health, systems evaluation, group decisions, international conflict resolution, new technologies, thinking, and ethics [21]. The Analytical Hierarchical Process is based on the structure of the hierarchical model (representation of the problem by identifying goals, criteria, and sub-criteria) [22,23].

Small and medium-sized enterprises (SMEs) in the mining industry are relevant actors in the sector and essential generators of employment [5]. However, as with this type of company in other sectors, the literature shows that mining companies need more efficient management [24] and suffer from a lack of capabilities and resources to develop satisfactorily [25]. The challenges posed for companies in the mining sector are several; to be viable, they must be able to respond to the economic and productive needs posed by the juncture [26]. In all organizations, there are problems of different kinds. However, they have a common denominator: the need to choose between various alternatives, which must be evaluated based on several criteria [27].

The main objective of this study is to identify and prioritize the different criteria and sub-criteria that should be considered when selecting an explosives supplier for small and medium-sized mining companies. To prioritize these criteria to support the most convenient decisions, the AHP methodology is used and a sample is taken of small and medium-sized mining companies in the Coquimbo Region, Chile.

An in-depth literature review by the authors [28] revealed that several investigations have used multi-criteria techniques to define optimal mining methods for different ores. However, the available literature on analyzing criteria for selecting explosives suppliers is scarce. As we have pointed out, this is essential in the mining production cycle. Thus, the research results contribute to developing a prioritized ranking of criteria for supplier selection, which can be of significant importance in medium-scale mining planning.

2. Methods

The Analytic Hierarchical Process (AHP) is a multi-criteria method developed by Saaty (1977), which, since its inception, has been successfully used on several occasions [16]. The method is characterized by its simplicity and robustness, which allows its application to extend to several areas, including supply chain management, entrepreneurship, engineering, and marketing [29–31]. For the case of the present study, in the mining industry, the AHP methodology has significant advantages: (1) It allows the participation of different people or interest groups and generates consensus; (2) the methodology is easy to use and allows its solution to be complemented with mathematical optimization methods, avoiding researchers’ judgments; and (3) it does not require high volumes of respondents, allowing for the optimization of resources [32,33].

It is based on the Newtonian and Cartesian method, which seeks to solve a problem by decomposing it into factors, which can be decomposed into new elements down to the lowest level [34]. The method prioritizes the relative importance of a list of criteria (factors) through pairwise comparisons between elements by relevant experts using a nine-point scale, presented in Table 1. The number of judgments for constructing a matrix A is $n \times (n - 1)$, where n is the number of elements.

Table 1. Saaty’s fundamental scale for the AHP method.

Intensity of Importance on an Absolute Scale	Definition	Explanation
1	Equal importance	Two options contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	Applied when compromise is needed

The mathematical process begins to normalize and finds the relative weights of each matrix, as shown in Equation (1).

$$Aw = \lambda_{max} * w \tag{1}$$

The quality of the results of the AHP method is strictly related to the consistency of the pairwise comparison judgments. Consistency is defined by the ratio between the entries for a (Equation (2)) and the consistency index CI (Equation (3)).

$$a_{ij} \times a_{jk} = a_{ik} \tag{2}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

The final consistency ratio (CR) (Equation (4)), based on which it can be concluded whether the evaluations are sufficiently consistent, is calculated as the ratio of the consistency index (CI) and the random index, called RCI (Table 2). As a rule of thumb, an RCI value of 10% or less is acceptable [18,34]. We used the Expert Choice[®] software to obtain the analyses and parameters.

$$CR = \frac{CI}{RCI} \tag{4}$$

Table 2. Random rates as a function of matrix size (n).

Matrix Size (n)	2	3	4	5	6	7	8	9	10	11	12
Random consistency (RCI)	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54

Classification of Criteria and Sub-Criteria

Technical and operational criteria exist for deciding whether to purchase a product or service.

For acquiring a product or service, we identified 39 elements separated into criteria and sub-criteria based on an exhaustive literature review. This gave rise to 7 main criteria, presented in Table 3. Based on the works of [35–40], we established the following general criteria, shown in Table 3. The details of the criteria and sub-criteria are presented in Appendix A.

Table 3. General criteria.

Code	General Criteria
A	General background
B	Quality of products and services
C	Price and costs
D	Innovation
E	Relationship with the environment and communities
F	Customer–supplier relationship
G	Contractual compliance

Based on the construction of the hierarchical tree, a paired comparisons questionnaire was developed to establish priorities. The questionnaire consisted of 18 items and a total of 71 questions. The device was reviewed and validated by three experts before its application.

Each company (Table 4) was contacted to explain the study’s objective, and three professionals deciding whether to purchase explosives were defined among them.

A total of 18 valid surveys were received from 7 mining companies, representing 40% of the total number of companies.

The different criteria and sub-criteria are represented through a hierarchical tree (Figure 1), constructed by the various levels to which they belong.

3. Results

The reliability analysis was obtained by calculating Cronbach’s alpha, with a result of 93%. When the Cronbach’s α value is higher than 70%, it indicates that the data are acceptable and reliable [43,44].

Figure 2 shows the hierarchy of the main criteria concerning the overall goal, where the standard “relationship with the environment and communities” was the one with the highest percentage of preference when selecting an explosives supplier company, with 33.50%; followed by “quality of products and services”, with 21.70%; and in third place, “contractual compliance”, with 13.20%.

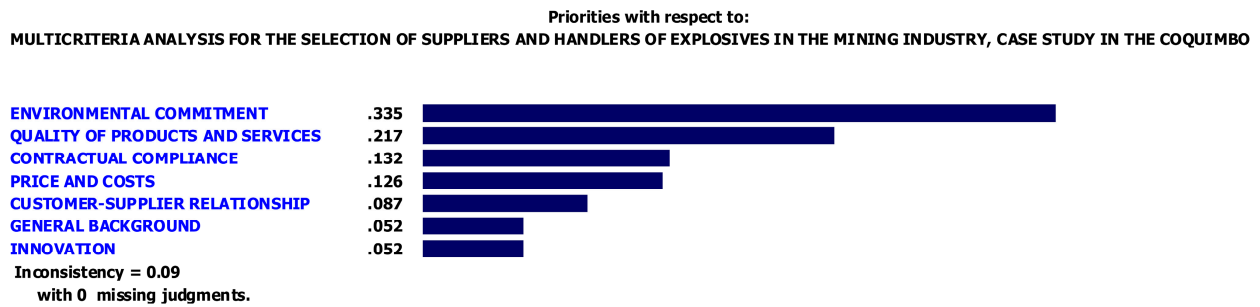


Figure 2. Hierarchy of main criteria.

Figure 3 shows the overall weights of each of the criteria concerning the overall goal, where “sustainability in the processes”, “commitment to the communities”, and “environmental pollution” were the criteria that represented the highest weight for the selection of explosives suppliers, at 14.10%, with all of them belonging to the primary criterion called “relationship with the environment and communities”.

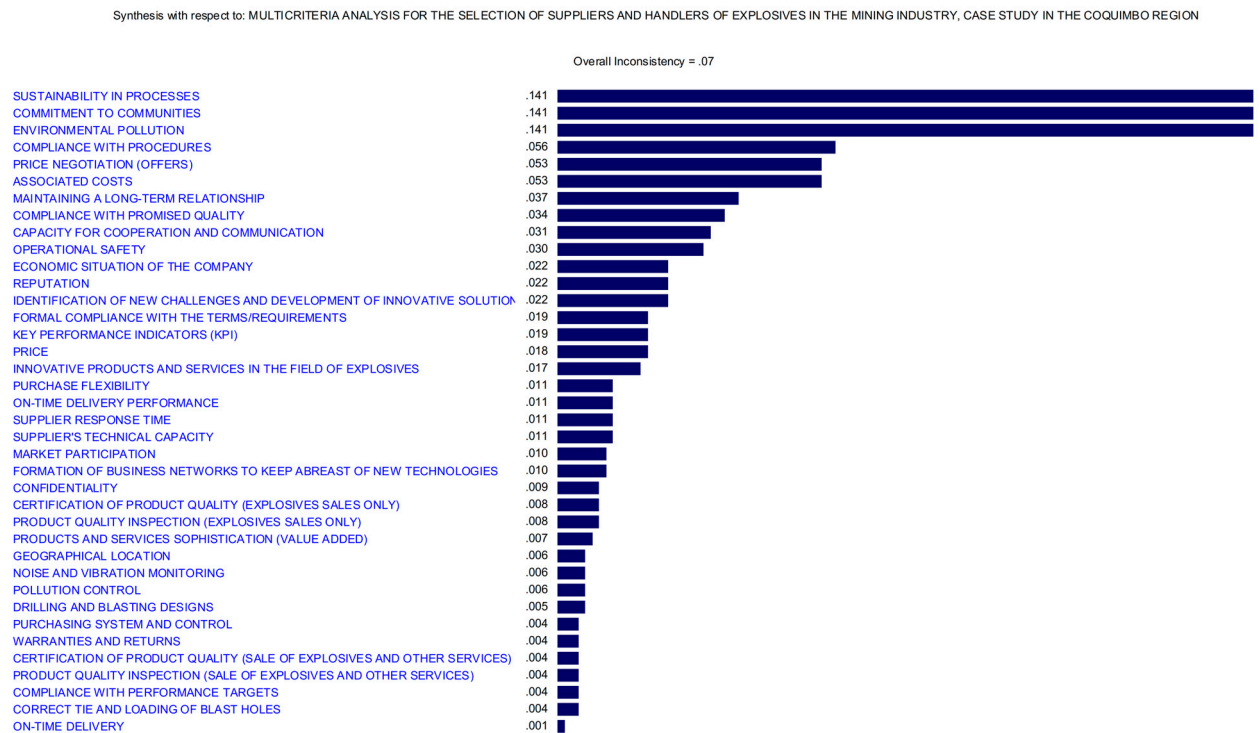


Figure 3. Global hierarchy of sub-criteria.

A performance sensitivity analysis was used to dynamically change the priorities of the objectives to determine how these changes affect the preferences of the criteria. The overall importance of the main criteria represented by vertical bars is shown on the horizontal

axis. Relative performance concerning any of the primary criteria is demonstrated by the intersection of the criteria’s line segment with the standard. Figure 4 shows the results of the sensitivity analysis.

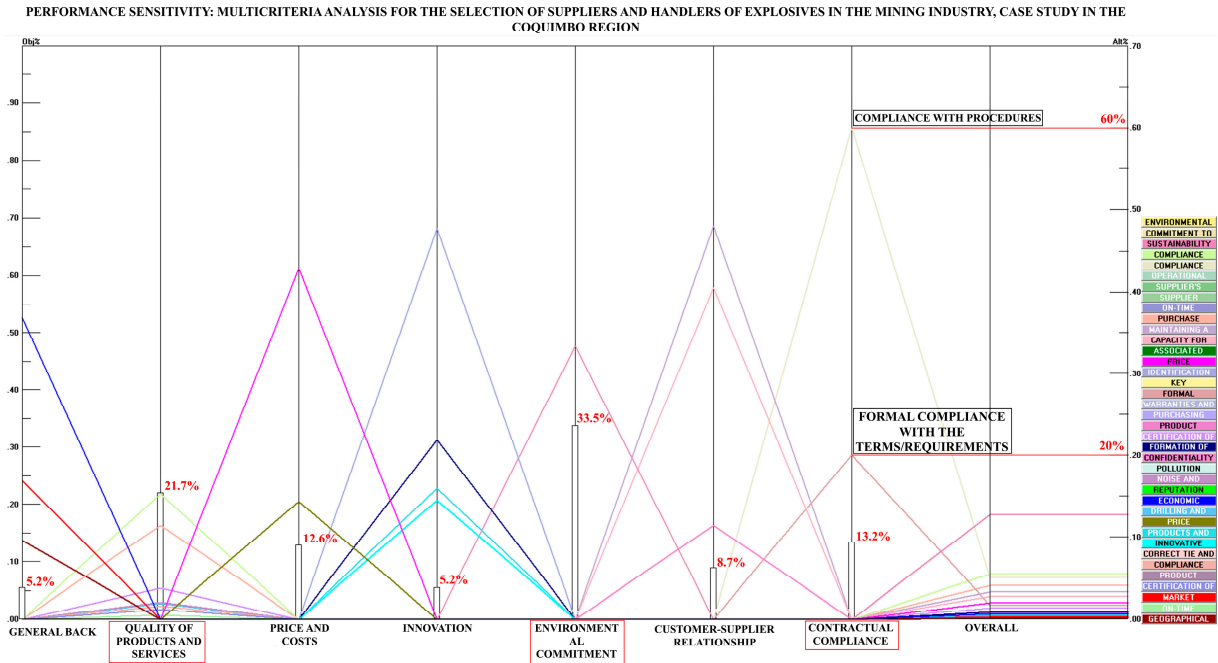


Figure 4. Performance sensitivity multi-criteria analysis.

Figure 5 shows the head-to-head sensitivity analysis, which shows how two criteria compare with each other concerning the evaluation criteria. In this analysis, the two options with the highest percentage of preference concerning the overall goal were compared, i.e., the criterion “sustainability in processes”, belonging to the criterion “relationship with the environment and communities”, and the criterion “compliance with procedures”, belonging to the criterion “contractual compliance”.

Weighted head to head between SUSTAINABILITY IN PROCESSES and FORMAL COMPLIANCE WITH THE TERMS/REQUIREMENTS

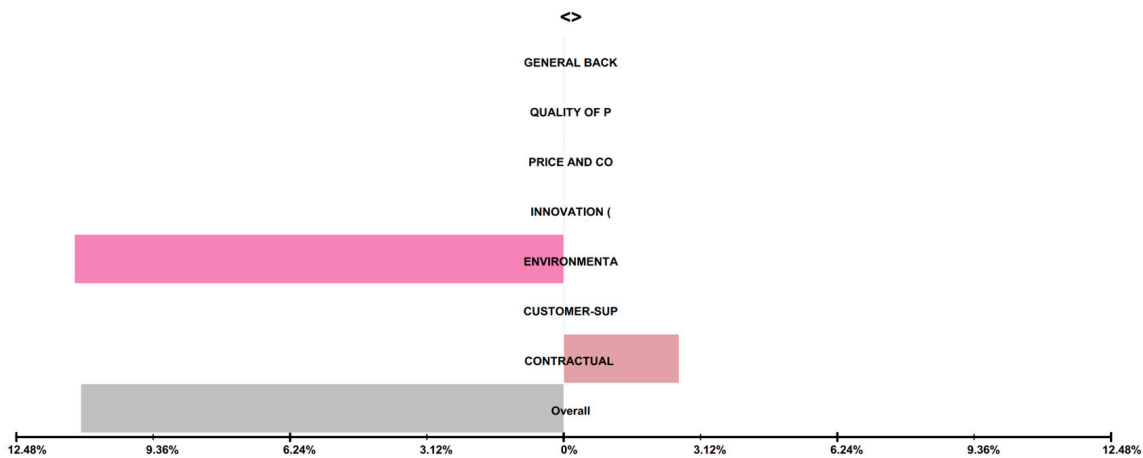


Figure 5. Weighted head-to-head between sustainability in processes and formal compliance with the terms/requirements.

Figure 6 shows the two-dimensional sensitivity analysis, which shows how two criteria compare with each other concerning the evaluation criteria. This analysis compared the criteria belonging to the “general background” and “innovation” criteria.

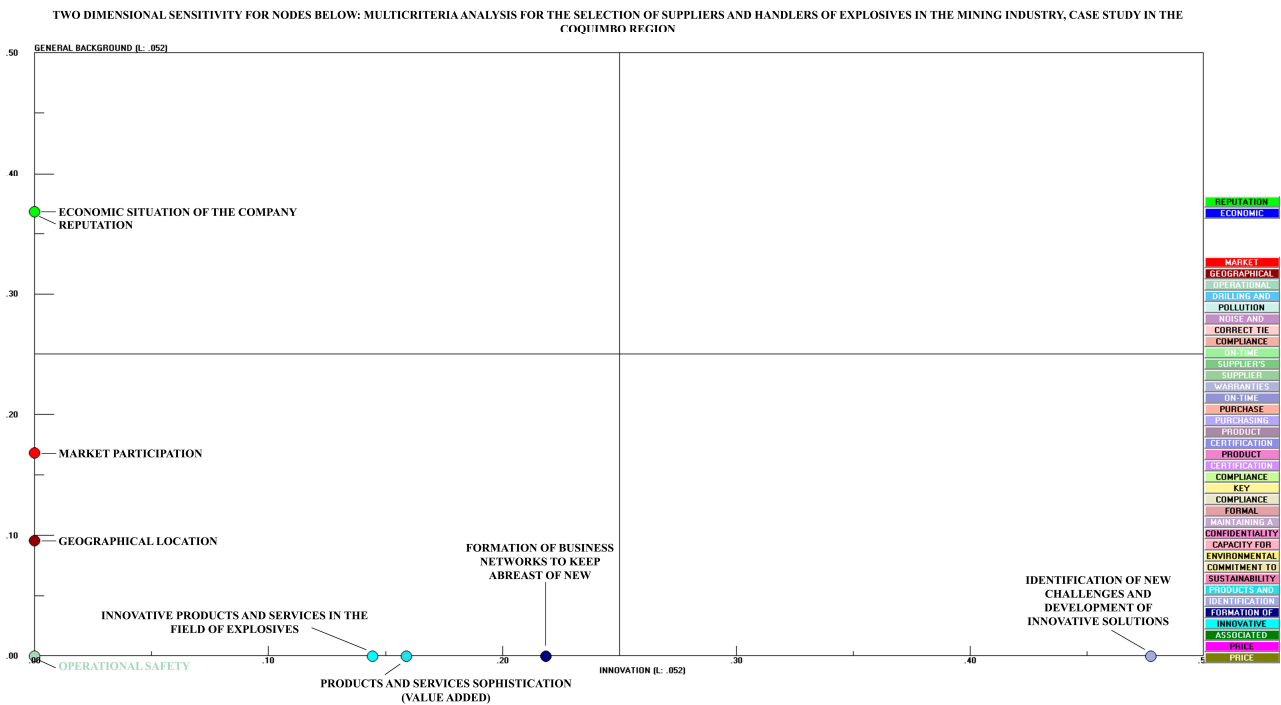


Figure 6. Two-dimensional sensitivity for nodes below.

For the present study, two different gradient sensitivity analyses were performed. The first case was carried out by varying one of the criteria with less importance, “general background”, with 5.2%. Figure 7 shows the result of the analysis. Even though the criterion’s importance increased to 28.5%, only one criterion had a negative trend—in this case, “sustainability in processes”. This speaks of the excellent consistency of the choice of criteria within the analyzed criterion. For the second analysis, we varied the most crucial criterion, “environmental commitment” (33.5%). When its importance was decreased by 25.3%, changes in the trends of the selected criteria were observed. These results show the excellent robustness of the criteria even when substantial changes are made in the criteria preference and allow for generalization of the results obtained. They continue to consolidate their position as the most important in selecting explosives suppliers.

From the results of the dynamic sensitivity analysis, we can indicate that there were three criteria with the best weight among the possibilities: “sustainability in processes”, “commitment to communities”, and “environmental pollution”. If we wanted to make the two most essential criteria equal in (global) participation, varying the criterion with the lowest priority—“general background” (5.2%)—it would be necessary to increase its participation to 28.4%, that is, a percentage variation of 23.2%, or almost a quarter of the preferences. This modification would achieve the values shown in Figure 8, which shows that even when the least important criterion suffered substantial variations in its importance, the most critical criteria continued to be “sustainability in processes”, “commitment to communities”, and “environmental pollution”. Two new criteria became essential: “economic situation of the company” and “reputation”, each with 9.6%. Based on the results, we can conclude the robustness of the analysis since a considerable variation in preferences was necessary for these criteria to change their position.

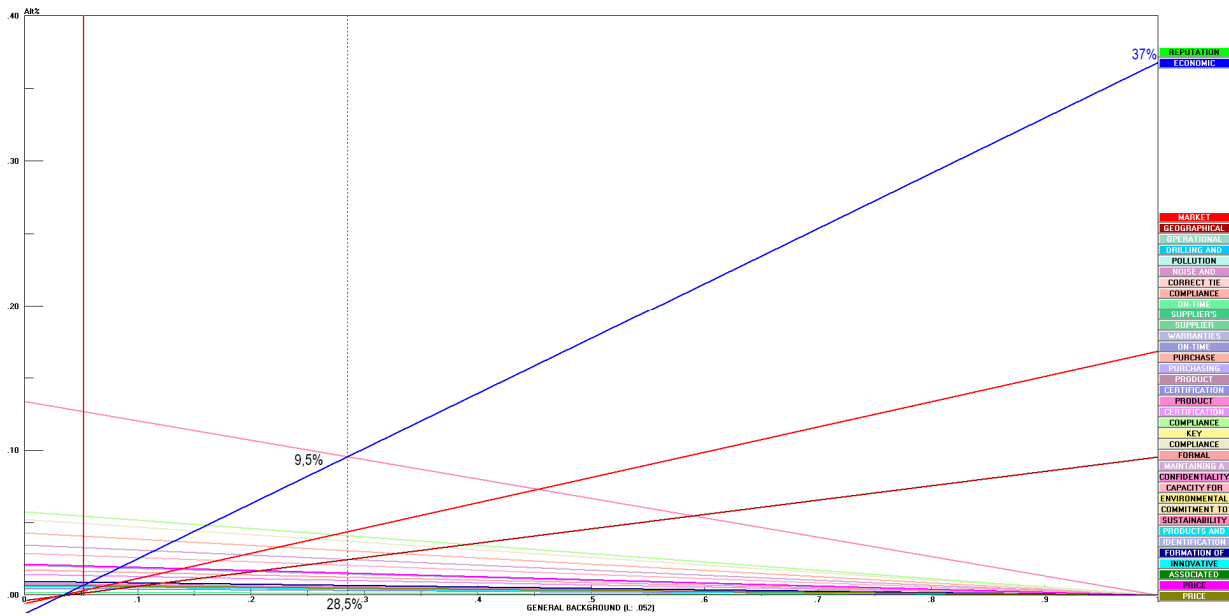


Figure 7. Gradient sensitivity analysis.



Figure 8. Dynamic sensitivity analysis.

4. Discussion

Concerning the overall goal of the seven main criteria, the criteria “relationship with the environment and communities” (33.5%) and “quality of products and services” (21.7%) were the criteria that were taken into account the most when selecting an explosives supplier, together comprising more than half of the total prioritization (55.2%) at the time the decision was made. The other two main criteria that followed were “contractual compliance and “price and costs”.

The main criterion with the most significant importance in the study was “relationship with the environment and communities”; the sub-criteria of “sustainability in processes”, “commitment to communities”, and “environmental contamination” were all equally important, as they each obtained 33.3%.

The sensitivity analysis shows that, concerning the overall goal, the three main criteria with the most significant overall weight were “relationship with the environment and communities”, at 33.5%; “quality of products and services”, at 21.7%; and “contractual compliance”, at 13.2%. The three sub-criteria with the highest overall weight were “environmental contamination”, “commitment to communities”, and “sustainability of processes”, with 14.1%, followed by “compliance with procedures”, at 5.6%, and “price negotiation with suppliers”, at 5.3%.

The results of the two-dimensional sensitivity analysis show that for the innovation criterion represented on the X-axis, between 45 and 50% of the prioritization was generated from “identification of new challenges” and “development of innovative solutions”, whereas the sub-criteria “networking with companies to learn about new technologies”, with 20–25%, and “innovative products and services”, with 10–20% of the priority, were located to the left of the central axis, so they were of lesser importance. On the other hand, on the Y-axis, it can be seen that the highest significance for the “general background” criterion was the sub-criteria of “economic situation of the company” and “company’s reputation”, both with 35–40% priority, whereas further down, with a lower focus, were the sub-criteria of “market participation”, with 15–20%, and, finally, “geographical location”, with less than 10% preference.

Based on the head-to-head analysis, two criteria with the highest weights were compared: “sustainability in processes” and “compliance with procedures”, belonging to the general criteria of “relationship with the environment and communities” and “contractual compliance”, respectively. The criterion with the most remarkable predominance (approximately 11%) was “sustainability of processes”, corresponding to the general criterion of “relationship with the environment and communities” of an explosives supplier company. In contrast, the importance of the sub-criterion of “compliance with procedures”, belonging to the “contractual compliance” criterion, was approximately 9%.

Currently, large-scale mining in Chile provides not only mineral extraction but also development, and it does so with intense care for the environment; therefore, mining companies’ relationship with the environment surrounding them is essential to maintaining socially acceptable operations.

The results of this research coincide with the objectives of modern and responsible mining, which reflect that the decision-making of small and medium-sized mining companies in the Coquimbo Region when selecting a supplier of explosives is in line with a vision and mission to minimize the impact on the environment in which they operate. In addition, this leads to the development of the communities with which it interacts and, thus, generates mining. The study presents a model to assist in decision-making that can be replicated in other regions of the country, where there are also small and medium-sized mining companies with environments involved in the development of mining.

Finally, over the last few decades, mining companies have advanced in their knowledge of and awareness about balancing their economic needs with environmental considerations and the cultural traditions of the people living where they operate. In this sense, more constructive relationships have developed between the extractive industry and the affected communities in recent years based on respect, trustworthy commitment, and decision-making for mutual benefit. According to the results obtained in this research, the decision-making of small and medium-sized mining companies in the Coquimbo Region is moving towards sustainable mining.

5. Conclusions

There is no doubt that supplier selection is a complex process. Several internal and external factors can influence decisions. Therefore, it is essential to consider a management tool that facilitates these processes. Our results show the importance of some elements over others, even when we performed sensitivity analysis.

In these new times, the mining industry must address exciting challenges in terms of sustainability, focusing on the economic, social, and environmental points of view.

Therefore, it is essential to establish criteria for companies in this industry to operate sustainably. Thus, it can be shown that the most crucial criterion considered by SMEs of the mining industry in the Coquimbo Region was “relationship with the environment and communities” due to the national situation that exists between mining companies and communities, in addition to the momentum that environmental movements have gained in Chile, causing an increase in environmental standards and coexistence from the social point of view, where the ecological requirements are increasingly more extraordinary and more demanding, in addition to the fact that if these requirements are not met it could lead to a cease of activity or definitive closure.

The second most important criterion was “quality of products and services”, and these are also related to organizational performance, since it has been established that SMEs in the mining industry in the Coquimbo Region seek to establish conditions that allow them to be more productive and efficient in achieving their objectives. The third most important criterion was “contractual compliance”, which involves integrating mining SMEs in the Coquimbo Region with social and environmental issues to develop and be a driving force in the sustainability of the mining business.

The criterion with the most minor relevance was “innovation”. Based on this context, we can conclude that innovation in mining SMEs in the Coquimbo Region is not so important when selecting an explosives supplier, since there are no funds to invest in innovation, unlike large-scale mining, which does have them and sees innovation as an essential opportunity to optimize its processes in the medium or long term. In this case, SMEs in the mining industry in the Coquimbo Region do not risk their production but carry out their unitary operations through traditional processes. This may be because mining SMEs in the Coquimbo Region have significantly higher production costs than large mining companies, have greater financial vulnerability, and face more significant limitations in terms of productivity due to a smaller productive scale, low competitive access, etc. In addition to this, another conditioning factor is that this segment is generally required to comply with the same regulations as large mining despite having a clear difference in productive and operational scales. Thus, the financial and human resources that must be allocated to their compliance impact their operating costs and productivity, and there are no public policies to support their compliance and limit further development.

Another critical point was obtained from the sensitivity analysis, where, when the preference of the criteria varied, the criterion “compliance with procedures” remained at the top of the hierarchy in most of the scenarios analyzed, which demonstrates the robustness of the model since the main criteria were relatively insensitive to the simulated changes.

This study covered SMEs in the mining industry in the Coquimbo Region; therefore, its results are of interest to managers or owners of mining supplier companies, highlighting the factors in which they should work to increase their chances in the mining business. Managers should concentrate on sustainability and corporate social responsibility, for which ISO 45001 or ISO 26000 certification may be a successful strategy. In addition, our results suggest the importance of sustainable mining, for which establishing a management control system over these processes may be critical. Public policy plays an important role, as it should focus on supporting small and medium-sized mining companies to achieve certification and the implementation of management systems.

Future research could study whether the criteria studied impact the performance of supplier organizations or mining companies. It would also be interesting to analyze how the environment or communities may perceive the selection criteria and whether they will be in line or far from the companies’ point of view.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Criteria A.

Code	Criteria A
A ₁	Economic situation of the company
A ₂	Market participation
A ₃	Reputation
A ₄	Geographical location

Table A2. Criteria B.

Code	Criteria B	Code	Criteria B
BA	Explosives sales only	BB	Sale of explosives and other services
BA _A	Product quality	BB _A	Product quality
BA _{A1}	Compliance with promised quality	BB _{A1}	Compliance with promised quality
BA _{A2}	Quality certification	BB _{A2}	Quality certification
BA _{A3}	Quality inspection	BB _{A3}	Quality inspection
BA _B	Service quality	BB _B	Service quality
BA _{BA}	Purchasing and delivery services	BB _{BA}	General services
BA _{BA1}	Purchasing system and control	BB _{BA1}	On-time delivery
BA _{BA2}	Purchase flexibility	BB _{BA2}	Compliance with performance targets
BA _{BA3}	On-time delivery performance	BB _{BA3}	Correct tie and loading of blast holes
BA _{BB}	Post-sales services	BB _{BB}	Technical support and safety
BA _{BB1}	Warranties and returns	BB _{BB1}	Noise and vibration monitoring
BA _{BB2}	Supplier response time	BB _{BB2}	Pollution control
BA _{BB3}	Supplier's technical capacity	BB _{BB3}	Drilling and blasting designs
		BB _{BB4}	Operational safety

Table A3. Criteria C.

Code	Criteria C
C1	Market-appropriate pricing
C2	Price negotiation
C3	Associated extra costs

Table A4. Criteria D.

Code	Criteria D
D1	Innovative products and services in the field of explosives
D2	Formation of business networks to keep abreast of new technologies
D3	Identification of new challenges and development of innovative solutions
D4	Sophistication of products and services (value added)

Table A5. Criteria E.

Code	Criteria E
E1	Sustainability in processes
E2	Commitment to communities
E3	Environmental pollution

Table A6. Criteria F.

Code	Criteria F
F1	Capacity for cooperation and communication
F2	Confidentiality
F3	Maintaining a long-term relationship

Table A7. Criteria G.

Code	Criteria G
G1	Formal compliance with the terms/requirements
G2	Compliance with procedures
G3	Key performance indicators (KPIs)

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