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Evaluation of Mine Reclamation Criteria using Delphi-Fuzzy Approach

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Abstract

The mining and mineral industry has an important role in supporting the sustainable development of countries. Many countries rely on the income derived from natural resources but exploitation of the natural resources may affect the environment and destroy the ecosystem. The mining activities usually affect the surrounding lands and ecosystems. The natural, social, and economic environments are parts of this ecosystem that are directly involved in these activities. In order to reduce the environmentally destructive effects of mining on the ecosystem, some important measures must be taken to minimize the negative impacts of mining and the related industries. In this work, for the first time, a study is conducted to define and categorize the reclamation criteria in three largest iron ore mines. During this research work, an attempt is made to establish, define, and evaluate forty reclamation criteria. Since the number of criteria is high, in order to adopt the best practice in a mine reclamation program, these criteria should be prioritized. The defined criteria are ranked by the mining experts, mining managers, and related university professors according to their experience and knowledge. The collected raw data is evaluated, processed by the Delphi-Fuzzy process, and finally, analyzed using the multi-criteria decision-making method. The prioritized criteria can provide the authorities with a guideline to start a reclamation planning based on the mining and environment requirements and budgeting and also to make the most fruitful, effective, and low-cost decisions.

1. Introduction

Mine reclamation was first introduced in USA, aiming to rehabilitate the mining sites over the country through the elimination of risks, restriction of production and recycling of harmful materials, and physical, chemical, and biological rehabilitation of the sites.

Nowadays, in the developed countries such as USA, Canada, and Australia, the details of mine closure are the inherent component of the successful mining projects, and the reclamation of mining sites along with relevant procedures has been legitimized. In such countries, the environmental protection is practical and feasible with the minimum cost or even sometimes at no cost owing to the advanced pollution and contamination prevention plans [1].

Mine reclamation has grown from the fields of agriculture (including soil science) and forestry. The traditional land reclamation involves planting the trees in the affected lands. However, this can only be done once the destroyed land has been fully reclaimed [2].

Reclamation is the term that is used in this paper. In general, reclamation refers to the activities carried out to prepare the mined-out lands for the re-use and rehabilitation [3, 4]. Such activities do not necessarily restore the land to its former or original form and conditions (prior to mining) but return the affected land to a condition and to the productive use similar to the pre-mining conditions [5]. The restoration, rehabilitation, reclamation, and remediation terms are often used interchangeably. Rehabilitation is to repair the ecosystem processes, productivity, and services without necessarily achieving the return to the pre-disturbance conditions. Land rehabilitation will prevent the continued environmental deterioration and is

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consistent with the surrounding aesthetic values. Reclamation is the physical stabilization of the land into a non-erodible state, and remediation is the process of correcting a specific problem, thereby, reversing or avoiding the damage to the environment (Table 1). Within the mining context, restoration is synonymous with rehabilitation and is defined as the progressive activity related to the recovery of the original ecosystem. In other words, it is a process by which the impacts of mining on the environment are reduced through the reconstruction of a stable land surface followed by revegetation or development of an alternative land use in the reconstructed land form [6].

Understanding the ecosystem degradation processes can guide through the treatments that can be used to assist in the recovery of large disturbances; however, they continue to be based on the historical treatments. Understanding how the natural recovery processes operate allows new systems for mine reclamation to be developed [6].

Table 1. Definitions and explanations of different restoration-related concepts [6].

Concept	Definition
Remediation	To remedy is to "make good''. The process of correcting a specific problem, reversing or avoiding the damage to the environment
Reclamation	To reclaim is to bring back the land to a proper state or to provide a suitable substitute; the physical stabilization of the terrain to bring back the land to a proper state. Similar to restoration but focuses on one aspect of the ecosystem services
Rehabilitation	To rehabilitate is to restore close to a previous condition or status, not expected to bring the land back to perfection, not as intact or original as a restored land; the establishment of a stable and self-sustaining ecosystem.
Restoration	To restore is to bring back the original to an intact state; the process of rebuilding the ecosystem that existed prior to the disturbance

Different parts of a mining area including pit, waste dumps, and tailing dams will be covered by the reclamation activities. In fact, reclamation is not an activity distinct from design, planning, and mining but it is regarded as a component of mining activity that begins with the design and continues to the mining stage [7].

The history of long-term mining activities and successful reclamation of destructed areas [8, 9] shows that the decommissioning of mine sites and mine closure followed by mine reclamation require technical planning and managerial actions along with considering the sequence of activities [10].

The selected optimal reclamation method is one of the most important factors in the open-pit mine design and production planning as the pit location and depth and the economic requirements affect the determination of the reclamation method [11].

The background of mining activities in the past was not satisfactory due to the negative impact and disturbance on the environment after mine closure; of course, it does not mean the mine operators' carelessness.

Different components of mining activities including exploration, extraction, and processing induce extensive physical, chemical, and biological changes in the environment due to the nature and characteristics of the activities [12].

Each mine has a limited life span due to the limited nature of the resources being extracted. Eventually, the resources are exhausted or the mine reserve is reached, which is no longer profitable to extract for any number of reasons. This changes the land during the mine life span.

In many cases, the mining sites lie within the residential and agricultural lands or natural habitats, intensifying the contradiction between land use and environmental protection. Therefore, the implementation of environmental management of mines to minimize the adverse effects of mining activities on the environment and also the planning for reclamation of mine sites after the completion of mining activities have a great importance.

The operation of large mines has not yet been finished in Iran, and reviewing the laws and regulations through this study shows that there are no specific instructions, requirements or regulations for the reclamation of mining sites in this country. In the Environmental Regulations of Mining Activities, it is specified that the owner of the mine operation license will be committed and responsible for mine reclamation after mine closure.

Reviewing the previous research works indicate that reclamation has been considered as one of the mining phases and it is not necessarily a field of science [13]. In order to have a successful land reclamation, the basic activity is to improve and restore the land remained after mine closure [14]. Recultivation with regard to the characteristics of waste [15] and non-hazardous materials [16] is one of the best methods for the stabilization of waste dumps, tailings dams, pollutant and contaminant mitigation, and improvement of landscape.

During the post-closure period, the human involvement in natural sequence will speed-up the reclamation progress [17]. One of the most significant physical elements involved in the reclamation is the soil type. The major criterion for accomplishment of the reclamation objectives is to have an intact uncontaminated soil [18]. In the areas with a very poor soil for plant growth, the proper use of nitrogen helps to stabilize the plant and herbaceous species, and as a result, the exotic perennial and biennial plant species will be observed within a short period of time [17].

The capability of the destructed soil for organic carbon accumulation, carbon elimination from atmosphere, soil quality improvement, and reaction and restoration of biological population followed by site reclamation are often unknown [19]. The soil nature and evaluation of soil quality, which provide the context for biological, chemical and physical processes, are considered as important factors for making a decision on reclamation [5, 20]. In the recent decades, wetlands have been regarded as one of the most important components of the ecosystem after completion of the mining activities [21]. However, the role of wetlands in the mitigation or elimination of contaminants resulting from the mining activity is not properly regarded in the reclamation planning and rehabilitation of mine sites.

The major objectives of mine reclamation are environmental impact and risk mitigation, safety improvement, rehabilitation of lands (affected by mining activities), and water and socio-economic resources of site after the completion of mining activities [22]. Since the number of criteria are high, in order to adopt the best practice in providing the reclamation program, these criteria should be prioritized.

2. Materials and Method

2.1. Studied area

In this research work, three largest iron mines in Iran including Golgohar in the Kerman Province, Sangan in the Khorasan Province, and Chadormalu in the Yazd Province were selected for definition of the reclamation criteria. These three large mining-industrial complexes are located in hot arid regions with similar ecosystems.

2.1.1. Golgohar Mine

The Golgohar mine consists of six separate anomalies in the Kerman Province at the 55° 19′ E longitude and the 29° 7′ N latitude. The biggest anomaly of this large mine is anomaly 1, and the operation life of the anomaly has been estimated to be 30 years. The annual mining plan is the extraction of 5,000,000 tons of iron ore [23].

The Golgohar ore body is located in a semi-arid area surrounded by mountains with an elevation over 2500 m. Vegetation of the area is very sparse and mostly in the form of bushes and wild xerophytic plants. The dry and arid climate has caused extensive fluctuations in temperature during different seasons and during the day and night times [24].

2.1.2. Sangan Mine

The Sangan iron mine is located in the Khorasan-e Razavi province at the 60° 16′ E longitude and the 34° 24′ N latitude, and consists of three anomalies. The average elevation of the area from the sea level is 1000 m. The project site is located in a semi-arid area with a predominantly hot and dry climate. The average annual temperature is 16.3 °C. The average wind speed is 19.1 Km/h, chiefly blowing northerly and northeasterly during the summer. The maximum wind speed occurs in May to October [25].

2.1.3. Chadormalu Iron Mine

The Chadormalu iron mine is located in the Yazd Province at the 32° 17′ N latitude and 55° 30′ E longitude (Figure 1). The maximum depth of the deposit from the ground is 310 m. It consists of four iron ore anomalies with an elevation of 150-250 m higher than the surrounding area, and three northern anomalies join in depth, forming the northern ore body containing 80% of the reserve. Due to the vicinity to the Markazi and Lut Deserts, the area has a hot and dry climate with an average temperature of 20.8 °C [24].

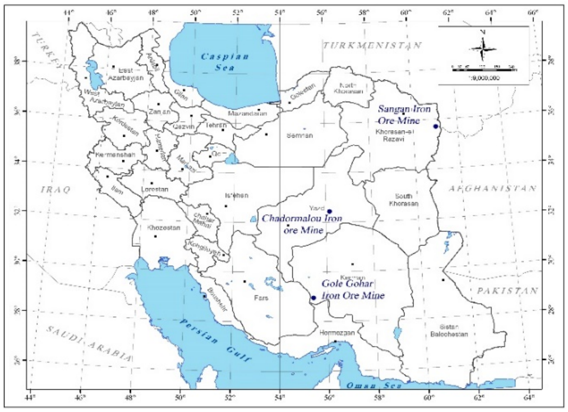

Figure 1. Locations of the three iron mines in the studied area.

2.2. Definition of reclamation criteria

Decision-making involves setting the right goals, determining different possible solutions, assessing the solution feasibility, dealing with the consequences of implementing each solution, and finally, selecting and implementing a solution. In order to define the best solution, suitable criteria should be established. The more detailed the criteria, the more accurate the results will be. In this research work, in order to establish the reclamation criteria, the literature review, field survey in two different seasons on type of ecosystem of the studied area, mine site visit, and interview with experts were carried out. Forty criteria were developed in three categories including natural, social, and economic environments, all of which were qualitative. Since it was impossible to use mathematic models, in order to quantify the criteria and to make a multi-criteria decision, the Fuzzy Delphi Analytical Hierarchy Process (FDAHP) method was used [26].

The multi-criteria decision-making system has many applications; for instance, it is applied for the prioritization of abandoned mines for future planning [27] and the optimum use of lands after completion of the mining activities with different land use scenarios [28].

2.3. Decision-making group

In FDAHP, the minimum number of participating experts is 5 and the maximum one is 20 [26]. Plenty of studies reveal that the experience and technical knowledge of the selected expert group in the Delphi method helps the effectiveness of the method and accuracy of the results [29].

Twenty well-experienced experts were selected in three categories including 8 university professors with different expertise in the environment, mine, environmental health, phytology, and zoology, well-experienced experts in the mining activities with expertise in geo-environment, geology, environment, and mining, and executive managers of three iron mines mentioned above [30, 31].

2.4. Data collection

The opinions of the experts were collected through a close-ended questionnaire. In this questionnaire, 40 criteria were defined. The importance degree of the criteria was represented by (1), (3), (5), (7), and (9) for very low, low, moderate, high, and very high, respectively.

The purpose of designing this questionnaire and obtaining the opinion of experts is that "which one of the following criteria has a priority and to what extent?"

Since multi-criteria decision-making covers various disciplines [32], the criteria defined in this work were categorized into the natural, social, and economic environments.

A) The criteria in the natural environment include:

- Topography and landform (slope and land relief)
- Vegetation (density, composition, economic value, medicinal value, cultivation method, and final land use)
- Water (drainage pattern, quality, and quantity)
- Climate (precipitation, temperature, wind, and humidity)
- Soil (texture, water retention in soil, pH, organic matter percentage, nutrient percentage, physical and chemical properties, fertility, solubility, and erosion)
- Mine location (distance from residential areas, protected areas, sensitive ecosystems and historical heritage, former land uses, access roads, and extent of destructed land)

B) The criteria in the social environment include:
Native inhabitants, immigration, land ownership, employment, value of inhabitants' properties, safety, sanitation, and health

C) The criteria in the economic environment include:
Losing job, income, improvement of individual skills, and cost.
After collecting the completed questionnaires, the obtained data was analyzed based on FDAHP [26].

2.5. Delphi-fuzzy approach

In this research work, due to the quality of the criteria and the impossibility of using the mathematical models and taking advantage of the group communication structure and using the expert experience, the Delphi-fuzzy hierarchical analysis was employed as one of the most widely used multi-criteria decision-making methods. This method was used in this work because it was required to gather the people's opinions and judgments in a specialized area and provide a flexible framework that covers many obstacles related to inaccuracy. In this method, with one step of completing the questionnaire, all comments are collected, the opinions of all experts are respected, and there is no need to spend money.

In FDAHP, the forecasts presented by well-versed experts are stated in definite numbers. The Delphi method is a strong process depending on the collective opinions. This method is used when knowledge and information are not sufficient or when the application of rules, formulas, and mathematic models are limited. As a result, the opinions and judgments of the experts in a specific subject are collected; in other words, the judgment is left to the experts [26].

After collecting the completed questionnaires of criteria, the required data was extracted and the criteria were prioritized based on the following equations [26].

a) Calculate fuzzy numbers

$$a_{ij} = \left(a_{ij}.\delta_{ij}.\gamma_{ij}\right) \quad (1)$$

$$a_{ij} = \mathrm{Min}\left(\beta_{ijk}\right), k = 1 \ldots.n \quad (2)$$

$$\delta_{ij} = (\textstyle\prod_{k=1}^{n} \beta_{ij}{}^{\frac{1}{n}}), k = 1 \ldots.n \quad (3)$$

$$\gamma_{ij} = \mathrm{Max}\left(\beta_{ijk}\right), \quad k = 1 \ldots.n \quad (4)$$

In the above equations, β_{ijk} represents the relative importance of the parameter i over the parameter j according to the k[th] expert. a_{ij} *and* γ_{ij} are the highest and lowest importance values given by the respondents, respectively, and δ_{ij} is the geometric mean of the opinions. It is obvious that the fuzzy components are defined as$a_{ij} \leq \delta_{ij} \leq \gamma_{ij}$. The values of these components vary within {1/9, 9}. At this stage, the fuzzy pairwise comparison matrix of different parameters is computed as follows:

b) Fuzzy inverse matrix formation

$$\tilde{A} = [\tilde{a}_{ij}]\, \tilde{a}_{ij} \times \tilde{a}_{ij}\ \forall_{ij} = 1.2\ldots, \mathrm{n}$$

or:

$$\tilde{A}=\begin{bmatrix} (1.1.1) & (\alpha_{12}.\delta_{12}.\gamma_{12}) & (\alpha_{13}.\delta_{13}.\gamma_{13}) \\ \left(\frac{1}{\gamma_{12}}.\frac{1}{\gamma_{12}}.\frac{1}{\alpha_{12}}\right) & (1.1.1) & (\alpha_{23}.\delta_{23}.\gamma_{23}) \\ \left(\frac{1}{\gamma_{13}}.\frac{1}{\gamma_{13}}.\frac{1}{\alpha_{13}}\right) & \left(\frac{1}{\gamma_{23}}.\frac{1}{\gamma_{23}}.\frac{1}{\alpha_{23}}\right) & (1.1.1) \end{bmatrix} \quad (5)$$

The relative weight of the parameters is computed as follows:

c) Calculate the relative fuzzy weight of the parameters

$$\widetilde{Z_i} = \left[\tilde{a}_{ij}\ (\ldots (\tilde{a}_{in}\right]^{\frac{1}{n}} \quad (7)$$

$$\widetilde{W_i} = \widetilde{Z_i}((\widetilde{Z_i}(\ldots(\widetilde{Z_i})^{-1} \quad (8)$$

where:

$$\alpha^{-}{}_{\downarrow}1\ (\alpha^{\sim}{}_{\downarrow}2 = (\ \alpha_{\downarrow}1 \times\ \alpha_{\downarrow}2\ , \delta_{\downarrow}1\ \times\ \delta_{\downarrow}2\ , \gamma_{\downarrow}1 \times\ \gamma_{\downarrow}2\ )\ W^{-}{}_{\downarrow}i \quad (9)$$

where $\widetilde{W_i}$ is a linear vector showing the fuzzy weight of the i[th] parameter.

At this stage, in order to change the fuzzy parameters into the non-fuzzy parameters, the geometric mean of fuzzy parameters is computed and the weight of the parameters is stated by a definite Figure.

d) Non-fuzzy weighting of parameters

$$W_i = (\prod_{j=1}^{a} w_{ij})^{\frac{1}{3}} \quad (10)$$

4. Results and Discussion

A total of 30 questionnaires were sent to the expert group, and 20 filled out questionnaires were received. The data received through these questionnaires was extracted, classified, and used as the input data for FDAHP. The Fuzzy pairwise comparison matrix was computed, and the given value given to each criterion was compared by different experts. Table 2 shows one part of the experts' scoring table. Then a pairwise comparison matrix was formed corresponding to each one of the criteria for each expert (Table 3). In the next stage, the minimum, geometric mean, and maximum of each criterion were defined (Tables 4, 5 and 6).

Table 2. Expert's scoring table.

Parameter	Expert									
	1	2	3	4	5	6	7	8	9	10
Slope	7	7	9	7	5	9	7	7	7	7
Land relief	5	7	7	7	5	7	7	3	5	7
Plant density	9	7	7	5	5	5	7	9	7	3
Plant composition	7	5	7	3	7	3	9	7	5	3
Plant Medical value	7	5	3	3	3	1	3	5	3	1
Plant Economic value	5	5	5	7	5	5	3	7	7	3
Cultivated method	5	5	5	5	5	1	7	1	3	1
Final land use	5	7	5	9	7	3	3	9	5	3
Drainage pattern	3	7	7	3	3	5	3	5	7	3
Water quantity	5	5	7	9	5	7	7	7	3	5
Water quality	5	7	5	7	7	5	9	9	3	5

Table 3. Paired comparison matrix for expert No. 1.

Parameter	Score	Code	Sl	Rf	De	Cm	Mv	Ev	Pm	Pl	Dp	Qu	Qa
Slope	7.00	Sl	1.00	1.40	0.78	1.00	1.00	1.40	1.40	1.40	2.33	1.40	1.40
Land relief	5.00	Rf	0.71	1.00	0.56	0.71	0.71	1.00	1.00	1.00	1.67	1.00	1.00
Plant density	9.00	De	1.29	1.80	1.00	1.29	1.29	1.80	1.80	1.80	3.00	1.80	1.80
Plant composition	7.00	Cm	1.00	1.40	0.78	1.00	1.00	1.40	1.40	1.40	2.33	1.40	1.40
Plant medical value	7.00	Mv	1.00	1.40	0.78	1.00	1.00	1.40	1.40	1.40	2.33	1.40	1.40
Plant economic value	5.00	Ev	0.71	1.00	0.56	0.71	0.71	1.00	1.00	1.00	1.67	1.00	1.00
Cultivated method	5.00	Pm	0.71	1.00	0.56	0.71	0.71	1.00	1.00	1.00	1.67	1.00	1.00
Final land use	5.00	Pl	0.71	1.00	0.56	0.71	0.71	1.00	1.00	1.00	1.67	1.00	1.00
Drainage pattern	3.00	Dp	0.43	0.60	0.33	0.43	0.43	0.60	0.60	0.60	1.00	0.60	0.60
Water quantity	5.00	Qu	0.71	1.00	0.56	0.71	0.71	1.00	1.00	1.00	1.67	1.00	1.00
Water quality	5.00	Qa	0.71	1.00	0.56	0.71	0.71	1.00	1.00	1.00	1.67	1.00	1.00

Table 4. Part of the minimum matrix.

Criteria	Code	Sl	Rf	De	Cm	Mv	Ev	Pm
Slope	Sl	1.00	0.60	0.43	0.71	1.00	1.00	0.71
Land relief	Rf	0.43	1.00	0.33	0.43	0.60	0.43	0.60
Plant density	De	0.43	0.43	1.00	0.60	0.78	0.60	1.00
Plant composition	Cm	0.33	0.33	0.43	1.00	0.78	0.43	0.43
Plant medical value	Mv	0.11	0.11	0.11	0.11	1.00	0.20	0.33
Plant economic value	Ev	0.20	0.20	0.33	0.33	0.33	1.00	0.33
Cultivated method	Pm	0.11	0.14	0.11	0.14	0.20	0.14	1.00
Final land use	Pl	0.33	0.33	0.43	0.33	0.71	0.60	0.43
Drainage pattern	Dp	0.43	0.43	0.33	0.33	0.43	0.43	0.43
Water quantity	Qu	0.20	0.20	0.33	0.33	0.33	0.43	0.33
Water quality	Qa	0.43	0.56	0.43	0.60	0.71	0.43	0.71

Table 5. Part of the geometric mean matrix.

Criteria	Code	Sl	Rf	De	Cm	Mv	Ev	Pm
Slope	Sl	1.00	1.14	1.07	1.26	2.23	1.49	1.90
Land relief	Rf	0.88	1.00	0.94	1.11	1.96	1.31	1.68
Plant density	De	0.93	1.06	1.00	1.18	2.08	1.39	1.78
Plant composition	Cm	0.79	0.90	0.85	1.00	1.76	1.18	1.51
Plant medical value	Mv	0.45	0.51	0.48	0.57	1.00	0.67	0.85
Plant economic value	Ev	0.67	0.76	0.72	0.85	1.50	1.00	1.28
Cultivated method	Pm	0.53	0.60	0.56	0.66	1.17	0.78	1.00
Final land use	Pl	0.79	0.89	0.84	0.99	1.75	1.17	1.49
Drainage pattern	Dp	0.77	0.87	0.82	0.97	1.70	1.14	1.46
Water quantity	Qu	0.87	0.99	0.93	1.10	1.94	1.29	1.65
Water quality	Qa	0.93	1.05	0.99	1.17	2.06	1.38	1.76

Table 6. Part of the maximum matrix.

Criteria	Code	Sl	Rf	De	Cm	Mv	Ev	Pm
Slope	Sl	1.00	2.33	2.33	3.00	9.00	5.00	9.00
Land relief	Rf	1.67	1.00	2.33	3.00	9.00	5.00	7.00
Plant density	De	2.33	3.00	1.00	2.33	9.00	3.00	9.00
Plant composition	Cm	1.40	2.33	1.67	1.00	9.00	3.00	7.00
Plant medical value	Mv	1.00	1.67	1.29	1.29	1.00	3.00	5.00
Plant economic value	Ev	1.00	2.33	1.67	2.33	5.00	1.00	7.00
Cultivated method	Pm	1.40	1.67	1.00	2.33	3.00	3.00	1.00
Final land use	Pl	1.40	3.00	1.80	3.00	5.00	3.00	9.00
Drainage pattern	Dp	1.40	2.33	2.33	2.33	9.00	3.00	5.00
Water quantity	Qu	1.80	2.33	2.33	3.00	9.00	3.00	7.00
Water quality	Qa	1.40	3.00	2.33	2.33	9.00	5.00	9.00

Then the relative weights of the criteria were calculated as the fuzzy numbers Z and Zi for different criteria. Table 7 shows a part of this matrix. At this stage, the fuzzy numbers Z and Zi were calculated. The result obtained are shown in Table 8.

Then to form the non-fuzzy weight of the criteria, the geometric mean of the fuzzy numbers is calculated as follows (Wi) and the weight of the criteria is expressed as a definite number in Table 9.

Table 7. Paired comparison matrix.

Criteria	Code	Sl			Rf			De			Cm		
		Min	Power	Max	Min	Power	Max	Min	Power	Max	Min	Power	Max
Slope	Sl	1.00	1.00	1.00	0.60	1.14	2.33	0.43	1.07	2.33	0.71	1.26	3.00
Land relief	Rf	0.43	0.88	1.67	1.00	1.00	1.00	0.33	0.94	2.33	0.43	1.11	3.00
Plant density	De	0.43	0.93	2.33	0.43	1.06	3.00	1.00	1.00	1.00	0.60	1.18	2.33
Plant composition	Cm	0.33	0.79	1.40	0.33	0.90	2.33	0.43	0.85	1.67	1.00	1.00	1.00
Plant medical value	Mv	0.11	0.45	1.00	0.11	0.51	1.67	0.11	0.48	1.29	0.11	0.57	1.29
Plant economic value	Ev	0.20	0.67	1.00	0.20	0.76	2.33	0.33	0.72	1.67	0.33	0.85	2.33
Cultivated method	Pm	0.11	0.53	1.40	0.14	0.60	1.67	0.11	0.56	1.00	0.14	0.66	2.33
Final land use	Pl	0.33	0.79	1.40	0.33	0.89	3.00	0.43	0.84	1.80	0.33	0.99	3.00
Drainage pattern	Dp	0.43	0.77	1.40	0.43	0.87	2.33	0.33	0.82	2.33	0.33	0.97	2.33
Water quantity	Qu	0.20	0.87	1.80	0.20	0.99	2.33	0.33	0.93	2.33	0.33	1.10	3.00
Water quality	Qa	0.43	0.93	1.40	0.56	1.05	3.00	0.43	0.99	2.33	0.60	1.17	2.33

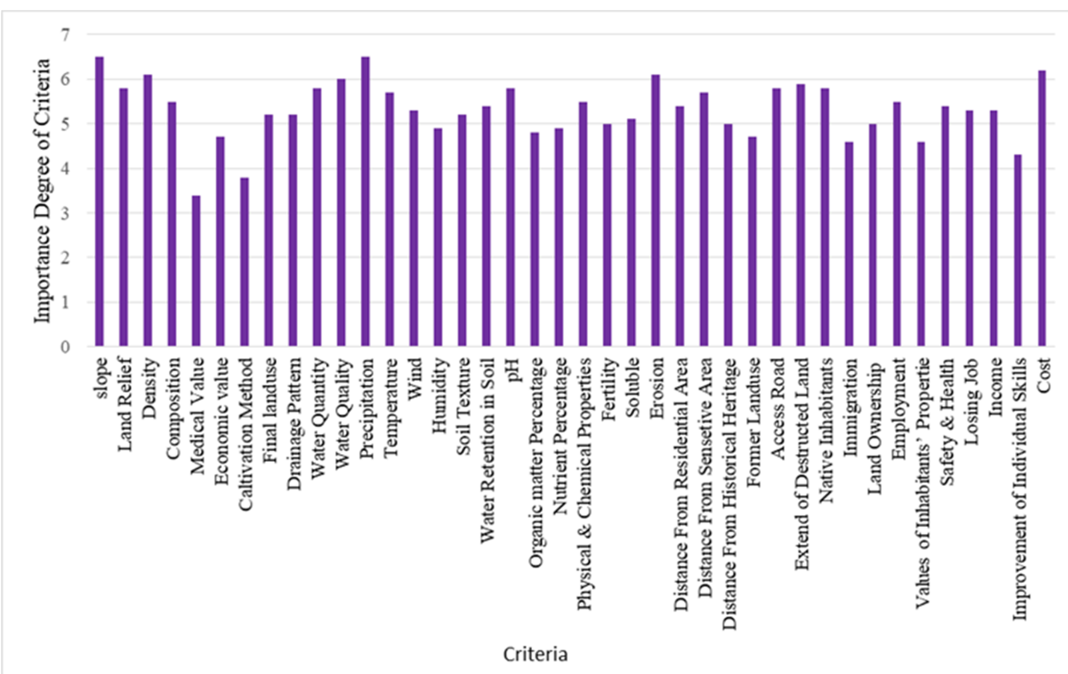

Figure 2. Percentage of expert's opinions about the importance degree of the criteria.

Table 8. Calculated fuzzy numbers Z and Zi.

Criteria	Z (Min)	Z (Ave)	Z (Max)	Zi (Min)	Zi (Ave)	Zi (Max)
Slope	9.3E-09	44603.36	9.09E+26	0.63	1.31	4.72
Land relief	0	280.9484	4.83E+25	0.44	1.15	4.39
Plant density	0	2949.283	8.76E+24	0.51	1.22	4.20
Plant composition	0	3.979874	4.4E+19	0.42	1.04	3.10
Plant medical value	0	6E-10	2.63E+11	0.14	0.59	1.93
Plant economic value	0	0.005595	3.19E+18	0.29	0.88	2.90
Cultivated method	0	3.07E-07	7.27E+12	0.15	0.69	2.10
Final land use	0	2.877761	5.34E+18	0.40	1.03	2.94
Drainage pattern	0	1.035994	5.21E+21	0.39	1.00	3.49
Water quantity	0	167.1929	7.73E+22	0.30	1.14	3.73
Water quality	0	2132.563	7.73E+23	0.50	1.21	3.96
Precipitation	0	8059.246	6.36E+23	0.32	1.25	3.94
Temperature	0	51.60276	2.24E+23	0.25	1.10	3.83
Wind	0	2.877761	2.41E+24	0.41	1.03	4.07
Humidity	0	0.009248	8.38E+19	0.25	0.89	3.15
Soil texture	0	0.165835	1.08E+19	0.20	0.96	2.99
Water retention in soil	0	1.769642	2.14E+19	0.21	1.01	3.04
Soil pH	0	101.1414	8.35E+23	0.23	1.12	3.96
Soil organic matter percentage	0	0.006526	7.18E+17	0.20	0.88	2.80
Soil nutrient percentage	0	0.003329	6.54E+16	0.18	0.87	2.63
Soil physical & chemical properties	0	2.877761	7.7E+22	0.23	1.03	3.73
Soil fertility	0	0.11511	3.46E+19	0.29	0.95	3.08
Soluble material in soil	0	0.652852	2.63E+20	0.23	0.99	3.24
Erosion	0	2998.031	2.53E+23	0.51	1.22	3.85
Distance from residential area	0	1.740868	6.79E+24	0.22	1.01	4.18
Distance from sensitive area	0	25.89985	3.08E+25	0.22	1.08	4.34
Distance from historical places	0	0.007611	1.23E+25	0.16	0.89	4.24
Former land use	0	0.006633	8.42E+19	0.25	0.88	3.15
Access roads	0	335.8155	9.02E+24	0.51	1.16	4.21
Extent of destroyed area	1E-10	1088.042	6.46E+25	0.55	1.19	4.42
Native inhabitants	0	327.6982	5.24E+21	0.45	1.16	3.49
Immigration	0	0.000725	5.19E+23	0.18	0.83	3.92
Land ownership	0	0.000261	6.23E+21	0.15	0.81	3.51
Employment	0	2.030548	1.08E+22	0.29	1.02	3.55
Values of inhabitants' properties	0	0.000261	4.04E+19	0.18	0.81	3.09
Safety & health	0	7.993781	2.24E+21	0.45	1.05	3.42
Losing job	0	1.035994	7.79E+22	0.21	1.00	3.73
Income	0	6.853378	1.17E+21	0.42	1.05	3.36
Improvement of individual skills	0	0.000224	3.56E+17	0.21	0.81	2.75
Cost of reclamation	0	4111.86	6.84E+25	0.47	1.23	4.42

As a general conclusion, based on the data presented in Table 10, 5.5% of the expert group gave a very low importance to the natural environment criteria, 19% low importance, 30.3% moderate importance, 30.5% high importance, and 14.7% very high importance. 6.7% of the expert group allocated a very low importance to the social environment criteria, 26.6% low importance, 25.9% moderate importance, 26.6% high importance, and 14.2% very high importance. 2.5% of the expert group allocated a very low importance to the economic environment criteria, 25% low importance, 32.5% moderate importance, 25% high importance, and 15% very high importance. Figure 2 shows the percentage of the expert's opinion about the importance of the criteria.

The following Figures show the comparison of importance between the criteria based on the expert's opinions. Figure 3 shows that only 20% of experts believe that slope has the maximum importance among the other criteria and rank it as a very important criterion. 60% of experts ranked both criteria (slope and land relief) at the very important level.

Table 9. Fuzzy and non-fuzzy weights.

Criteria	Code	Wij (Min)	Wij (Ave)	Wij (Max)	Wi
Slope	Sl	0.00	0.03	0.38	0.0378
Land relief	Rf	0.00	0.03	0.35	0.0312
Plant density	De	0.00	0.03	0.33	0.0330
Plant composition	Cm	0.00	0.03	0.25	0.0265
Plant medical value	Mv	0.00	0.01	0.15	0.0130
Plant economic value	Ev	0.00	0.02	0.23	0.0216
Cultivated method	Pm	0.00	0.02	0.17	0.0144
Final land use	Pl	0.00	0.03	0.23	0.0255
Drainage pattern	Dp	0.00	0.02	0.28	0.0266
Water quantity	Qu	0.00	0.03	0.30	0.0261
Water quality	Qa	0.00	0.03	0.31	0.0322
Precipitation	Pr	0.00	0.03	0.31	0.0279
Temperature	Te	0.00	0.03	0.31	0.0244
Wind	Wi	0.00	0.03	0.32	0.0287
Humidity	Hu	0.00	0.02	0.25	0.0213
Soil texture	Tx	0.00	0.02	0.24	0.0200
Water retention in soil	Wr	0.00	0.03	0.24	0.0207
Soil pH	pH	0.00	0.03	0.32	0.0242
Soil organic matter percentage	Om	0.00	0.02	0.22	0.0189
Soil nutrient percentage	Nm	0.00	0.02	0.21	0.0180
Soil physical & chemical properties	Pc	0.00	0.03	0.30	0.0232
Soil fertility	Fe	0.00	0.02	0.25	0.0227
Soluble material in soil	Sm	0.00	0.02	0.26	0.0216
Erosion	Er	0.00	0.03	0.31	0.0322
Distance from residential area	Re	0.00	0.03	0.33	0.0234
Distance from sensitive area	Ve	0.00	0.03	0.35	0.0242
Distance from historical places	Mh	0.00	0.02	0.34	0.0203
Former land use	Fl	0.00	0.02	0.25	0.0213
Access roads	Ar	0.00	0.03	0.33	0.0325
Extent of destroyed area	Da	0.00	0.03	0.35	0.0343
Native inhabitants	Nr	0.00	0.03	0.28	0.0293
Immigration	Em	0.00	0.02	0.31	0.0202
Land ownership	Lo	0.00	0.02	0.28	0.0181
Employment	Ep	0.00	0.03	0.28	0.0244
Values of inhabitants' properties	Vn	0.00	0.02	0.25	0.0183
Safety & health	Sh	0.00	0.03	0.27	0.0281
Losing job	Di	0.00	0.02	0.30	0.0221
Income	In	0.00	0.03	0.27	0.0275
Improvement of individual skills	Is	0.00	0.02	0.22	0.0188
Cost of reclamation	Co	0.00	0.03	0.35	0.0328

Table 10. Percentage of expert's opinions about importance degree of the criteria.

Main criteria	Percentage of expert opinions				
	Very low	low	moderate	high	Very high
Natural environment	5.5	19	30.3	30.5	14.7
Social environment	6.7	26.6	25.9	26.6	14.2
Economic environment	2.5	25	32.5	25	15

Figure 4 shows that 20% of experts believe that density has the maximum importance among the other criteria and rank it as a very important criterion. 15% of experts ranked the final land use, and 15% ranked the composition of flora at a very important level. Figure 5 shows that 20% of experts believe the water quality and the other 20% comment that water quantity has the maximum importance among the other criteria and rank it as a very important criterion. 15% of experts ranked the drainage pattern at a very important level.

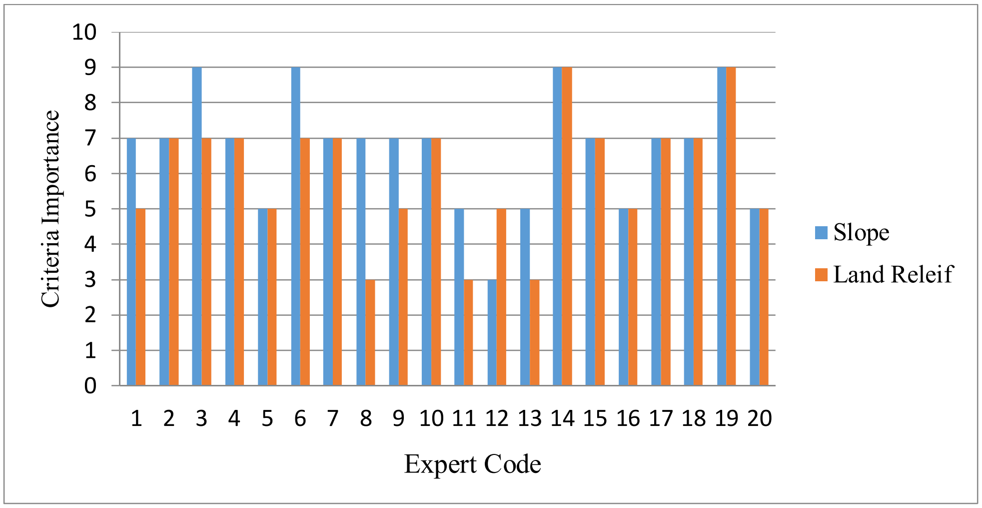

Figure 3. Comparison of importance between the topography and land relief criteria.

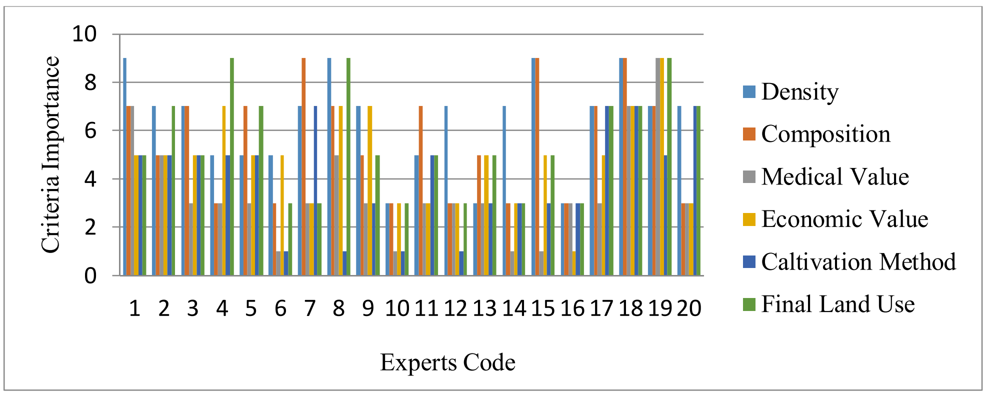

Figure 4. Comparison of importance between the vegetation criteria.

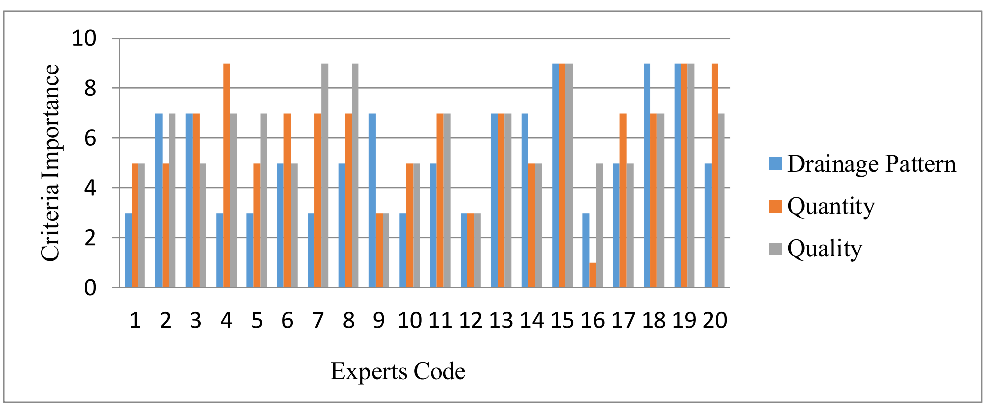

Figure 5. Comparison of importance between the water criteria.

Figure 6 shows that 10% of experts believe that each one of the four criteria in the climate category has the maximum importance and rank them as very important criteria. 35% of experts believed that among the climate criteria, precipitation had the maximum importance and ranked it as a very important criterion. Figure 7 shows that 20% of experts believe the physical and chemical properties and the other 20% comment that the soil nutrient percentage has the maximum importance and rank them as high important criteria. 15% of experts have the same opinion about the soil fertility, 15% about organic matter, and the other 15% about the pH and rank these criteria as a very important criterion.

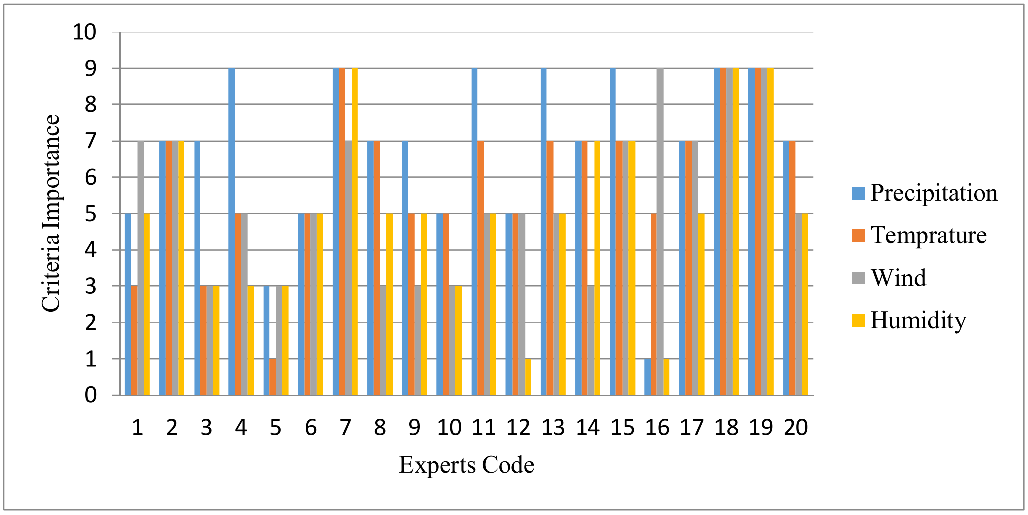

Figure 6. Comparison of importance between the climate criteria.

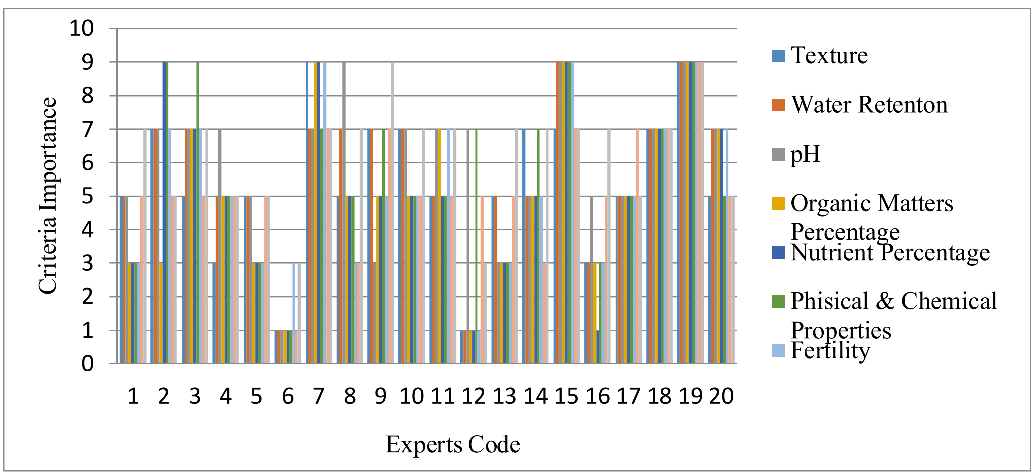

Figure 7. Comparison of importance between the soil criteria.

Figure 8 shows that 25% of experts believe that the distance from the environmentally protected area has the maximum importance and rank it as a very important criterion. 20% of experts also commented that the soil fertility of destructed land had the maximum importance and ranked it as a very important criterion. Figure 9 shows that 20% of experts believe that land ownership has the maximum importance and rank it as a very important criterion. 15% of experts also commented that the safety, sanitation, and health had the maximum importance and ranked it as a very important criterion. Figure 10 shows that 30% of experts believe that the reclamation cost has the maximum importance and rank it as a very important criterion. 20% of experts also commented that losing job has the maximum importance and ranked it as a very important criterion.

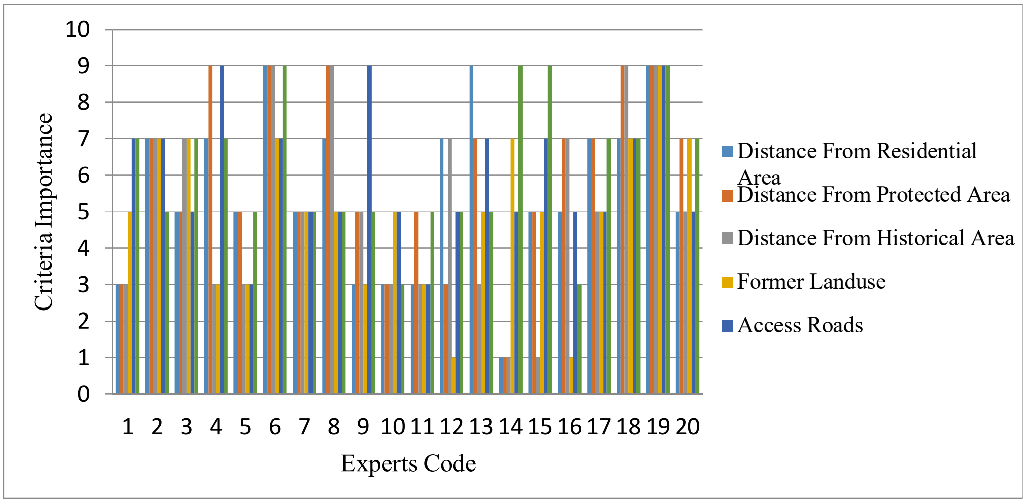

Figure 8. Comparison of importance between the mine criteria.

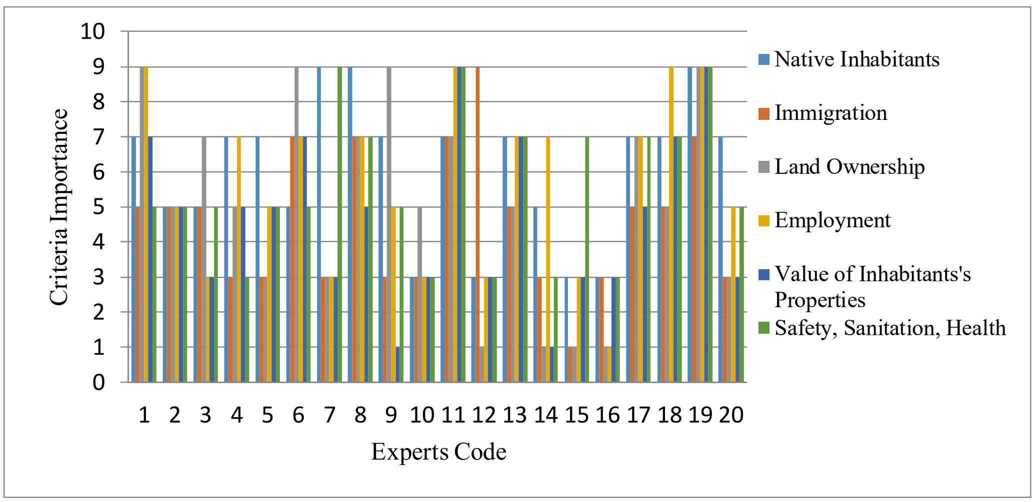

Figure 9. Comparison of importance between the social criteria.

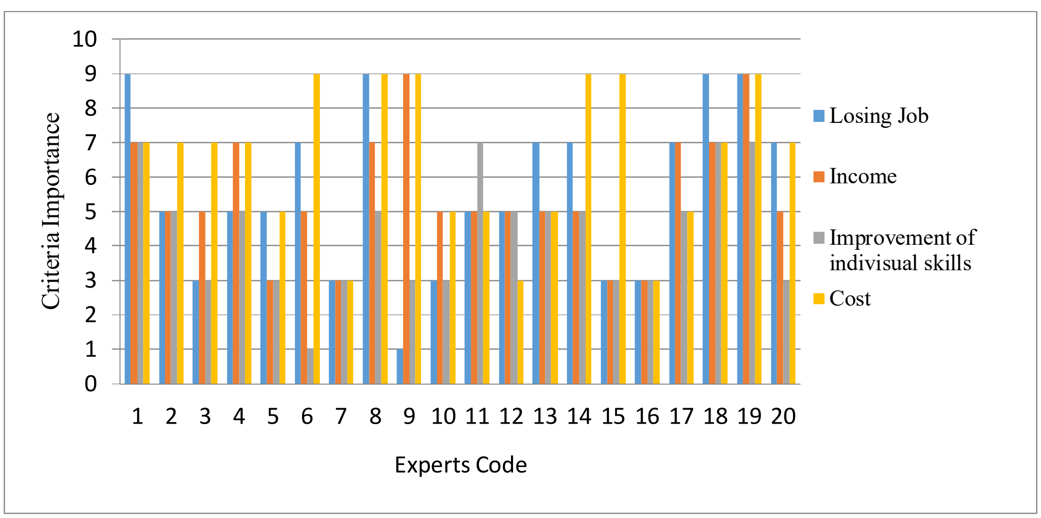

Figure 10. Comparison of importance between the economic criteria.

Based on the calculations presented in the previous chapter, the non-fuzzy weights of the criteria were determined and the criteria were prioritized as shown in Table 11.

Three criteria including slope, extent of destructed area, and vegetation density were assessed as the three most important criteria, while the least importance and preference was given to the cultivation method and medicinal value of the cultivated plants.

In the next step, considering the frequency and distribution of the criteria, another classification was done, and ultimately, 16 criteria were selected with the highest preference and priority in iron mine reclamation for the purpose of construction of reclamation model and instruction. The prioritized criteria are as follow:

- In the topography and landform category, slope and relief
- In the vegetation category, vegetation density and vegetation composition for cultivation
- In the water category, water quality and drainage pattern
- In the climate category, wind blow and precipitation
- In the soil category, soil erosion and soil pH
- In the mine location category, extent of destructed area and access roads
- In the social environment category, indigenous inhabitants of the area, and safety, sanitation, and health
- In the economic environment category, reclamation cost and income.

Table 11 shows the final results of this study, where forty criteria were prioritized based on the multi-criteria decision-making method.

Table 11. Priority of the criteria.

Priority	Criterion	W_i	Priority	Criterion	W_i
1	Slope	0.0378	21	Distance from sensitive area	0.0242
2	Extent of destroyed area	0.0343	22	Distance from residential area	0.0234
3	Plant density	0.0330	22	Soil physical & chemical properties	0.0232
4	Cost of reclamation	0.0328	23	Soil fertility	0.0227
5	Access roads	0.0325	25	Losing job	0.0221
6	Water quantity	0.0322	26	Soluble material in soil	0.0216
7	Erosion	0.0322	27	Plant economic value	0.0216
8	Land relief	0.0312	28	Humidity	0.0213
9	Native inhabitants	0.0293	29	Former land use	0.0213
10	Wind	0.0287	30	Water retention in soil	0.0207
11	Safety & health	0.0281	31	Distance from historical places	0.0203
12	Precipitation	0.0279	32	Immigration	0.0202
13	Income	0.0275	33	Soil texture	0.0200
14	Drainage pattern	0.0266	34	Soil organic matter percentage	0.0189
15	Plant composition	0.0265	35	Improvement of individual skills	0.0188
16	Water quality	0.0261	36	Values of inhabitants' properties	0.0183
17	Final land use	0.0255	37	Land ownership	0.0181
18	Employment	0.0244	38	Soil nutrient percentage	0.0180
19	Temperature	0.0244	39	Cultivated method	0.0144
20	pH	0.0242	40	Plant medical value	0.0130

The findings of this research work indicate that 16 criteria have priority over the other ones in iron mine reclamation in Iran. The prerequisites for the preparation of an executive plan for the iron mine reclamation based on the criteria studied in this research work depend on the mining method, mine decommissioning, and mine closure plan.

Lack of mine decommissioning and closure plan may yield adverse outcomes for the environment or for the socio-economic environment and local communities [4]. As a component of mine life cycle, the time factor has an essential role in the implementation of mine reclamation plans. The more the duration between the environmental damage and reclamation, the more the destruction of the existing resources. From the sustainable development viewpoint, it is better to consider the decommissioning of equipment and machineries as a component of operation activity and to allocate budget to it. The objective of mining decommissioning is to ensure that there will be no risk to the human health and the environment due to the existence of the physical and chemical pollutants and contaminants left over the area after the mining operation.

Depending on the mine type (metallic or non-metallic), mining method, ecosystem, climate, and legal requirements, different reclamation methods can be used for open-pit mines, which have their own advantages and disadvantageous. The major methods are the post-closure reclamation, temporary reclamation, progressive reclamation, and partial reclamation [33].

Regardless of the selected reclamation method, the most significant mine components for which the reclamation plan is provided are natural ecosystem (destructed vegetation), mine pit, waste dump, tailings dam, landfills, contaminated soils, contaminated surface water and groundwater, access roads, and industrial and semi-industrial sites.

Investigating the selected criteria shows that the Golgohar, Sangan, and Chadormalu mines have similar climate conditions and ecosystems. In these three mines, the highest degree of soil erosion is observed for the following reasons:

- Hot, dry, and arid ecosystem;
- Low precipitation (maximum: 200 mm/y);
- Very high rate of evaporation;
- Limited water quantity and shortage of water resources;
- Seasonal wind blow (wind blows with very high speed at the Sangan site most of the time throughout the year);
- Soil property (as a determinative factor for erodibility and infiltration rate);
- Topography or slope (as a determining factor for run-off water velocity and water energy, which cause erosion);
- Lack of vegetation with appropriate diversity and density.

In the above-mentioned mines, the surface soil is generally poor, which is the most fertile part with respect to nutrients, microorganisms, seeds, and roots of the plant [33, 34]. As a result, collecting and storing the surface soil of Sangan and Chadormalu (as one of the major components of reclamation in which biological, chemical, and physical processes occur) are practically useless [20]. The thickness of the surface soil at the Golgohar mine to be appropriate for the growth of plants reaches up to 0.5 m over some areas. However, no plan has been considered for collecting and storing such soil to improve and enhance the biological indicators and to perform revegetation [18].

In addition to the surface soil, the waste soil removed from the pit bottom and dumped at the waste dump is deprived of biological indicators such as microorganisms, nutrients, seeds, and roots of plants; therefore, the soil remediation plan should be implemented to restore and stabilize the soil and to perform revegetation.

As the investigations indicate, the soil pH within the Golgohar, Sangan, and Chadormalu mining sites is alkaline due to a hot and dry climate and the lack of precipitation. In the areas affected by the impact of the Sangan mining activities, the soil pH is 6.8-7.8 [35].

Most normal plants grow in a neutral soil. The most appropriate soil pH for the recultivation of plants is 5.1-6.1 [36]. The most significant role of the soil pH is to control the solubility of nutrient elements in soil; in other words, the absorption of nutrient elements by soil highly depends on the soil pH.

In addition to the above-mentioned issues, the land slope and design and the mining method in the three aforesaid mines were studied. In most open-pit mines, the bench slope varies from 55° to 80°, and in normal conditions, a slope of 65° is recommended at the beginning of the activity. The final pit of mine No. 1 in Golgohar is in the form of an ellipse with diagonals of about 2200 m × 700 m. This pit consists of 21 benches with an elevation of 15 m. The overall slope of pit walls is 38-45°. Access ramps to the mine were designed with a slope of 8% and a width of 25 m [23].

The Sangan deposit has the estimated dimensions of 8 × 26 km^2 consisting of three mining zones (eastern, central, and western zones) with magnetite as the major mineral. The slope of the pit wall varies between 42° and 55° [25].

In Chadormalu, the pit wall slope is 54.7% [37]. The slope and width of the access roads are 8% and 20-35 m, respectively.

Two factors that affect the cultivation of plants and production of sediments are the slope direction and steepness [33]. The slopes should be leveled and cultivated in order to be stabilized and to prevent surface soil erosion. It is necessary to create long steady slopes during the reclamation and to consider natural landforms of the adjacent areas in the slope design to avoid run-off flows with a higher speed on longer and steeper slopes [36].

In addition to the biological environment, the socio-economic criteria are investigated in the mine reclamation plan. Usually at the beginning of the mining activities, there are two groups of local communities in the area. The first group is the communities and villagers who live within the immediate affected area; they have to leave the area entirely. The second group is the local communities who live distant enough from the mining site but they are directly or indirectly dependent on the mining activities for earning their livings and expected to have benefit from the mining activities (through local jobs and employment in mining activities). The greatest impact and stress are imposed on the latter group during the mine closure and reclamation.

There is no village within the immediate area of the three above-mentioned mines. However, a considerable number of workforce have been sourced from the surrounding villages and small towns. They will lose their jobs during the mine closure and reclamation, and the families will be deprived of the services and secondary industries provided during the mine operation [4].

Based on the experiences, if the local communities are scrutinized in the EIA study of projects and entitled to be involved in decision-making, which affect their life [38], and if feasible economic alternative and proper change of land use are considered in the reclamation plan, then the mining activities and mine closure will impose a minimum negative effect on the local communities, sanitation, and health [39].

The mine site reclamation plan reduces the reclamation costs from the physical and financial aspects. The most important factors that should be regarded to forecast the reclamation costs are pit size, wall slope, and waste dump slope [40].

Generally, the reclamation costs cover earthworks, soil stabilization and revegetation, water treatment, waste disposal, waste and tailings dam management, clearing the area of buildings, equipment and utilities, monitoring, mine closure and reclamation plan, workforce, machineries, cost of maintenance after mine closure and reclamation, and direct and executive costs.

Up to 90% of the reclamation costs are related to earthworks (filling and grading) [36]. The best way for the minimization of costs is to change the slope and grade the area. Sometimes the minimization of grading changes at a site may result in the change of the project design or change in the project scale. The slopes greater than 30% should be modified to minimize erosion and run-off flows [41]. A portion of reclamation costs is supplied through selling the equipment and installations by mining companies [42].

5. Conclusions

Reclamation of mines in Iran is a requirement of mining activities and a crucial issue, even though major mines have not reached the end of their life span and the estimated reserve. However, this does not mean that no attention should be paid to the reclamation plan, as mine life span will eventually end and the owners and beneficiaries should consider the reclamation plan at present. For executing this activity, many variable criteria should be considered. Making decision with so many parameters would not be feasible since to adopt the best practice in the mine reclamation program, these criteria should be prioritized. Considering this issue in this work for the first time in Iran, the reclamation criteria were determined in three large iron ore mines. The criteria were evaluated using the Delphi-fuzzy process and prioritized based on the multi-criteria decision-making method. The findings indicated the priority of forty defined criteria where five most important and preferred ones were determined as slope, extent of destroyed area, plant density, cost of reclamation, and access roads.

The prerequisites for the preparation of an executive plan for the iron ore mine reclamation based on the criteria studied in this research work depend on the mining method, mine decommissioning, and mine closure plan.

The prioritized criteria provide the authorities with a guideline to start reclamation planning based on the mining and environment requirements and budgeting. The management quality is essentially subject to decision quality because the quality of plans and programs, efficiency of strategies, and quality of the results obtained from their application all depend on the quality of the decisions the manager makes.

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ارزشیابی معیارهای بازسازی معادن با استفاده از رویکرد دلفی- فازی

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چکیده:

معدن و صنایع معدنی در حمایت از توسعه پایدار کشورها نقش مهمی به عهده دارند. بسیاری از کشورها به درآمد حاصل از استحصال منابع طبیعی متکی هستند اما بهره برداری بی‌رویه از منابع طبیعی محیط را تحت تأثیر قرار داده و اکوسیستم را تخریب می‌نماید. فعالیت‌های معدنکاری معمولاً بر اراضی و اکوسیستم‌های اطراف آن تأثیر می‌گذارد. اکوسیستم طبیعی، اجتماعی و اقتصادی بخش‌هایی از اکوسیستم پیرامون فعالیت‌های معدنی هستند که به طور مستقیم تحت تاثیر این فعالیت‌ها قرار می‌گیرند. به منظور کاهش اثرات مخرب محیط‌زیستی ناشی از فعالیت معدنکاری بر روی اکوسیستم پیرامونی، باید اقدامات بسیار مهمی صورت گیرد تا اثرات منفی فعالیت‌های معدنی و صنایع وابسته به آن در دوران بهره‌برداری و زمان خاتمه عملیات به حداقل ممکن برسد. با در نظر گرفتن این موضوع، هدف از انجام این تحقیق، تعریف و طبقه‌بندی معیارهای بازسازی در سه معدن بزرگ کشور برای اولین بار می‌باشد. در طی این مطالعه، چهل معیار برای بازسازی معادن، تعیین، تعریف و ارزشیابی شدند. از آنجا که تعداد این معیارها زیاد است، برای اتخاذ بهترین روش برای برنامه‌ریزی احیا و بازسازی معادن، این معیارها باید اولویت‌دهی شوند. به این منظور معیارهای تعریف شده با توجه به تجربه و دانش متخصصان معدن، مدیران اجرایی و اساتید دانشگاه طبقه‌بندی شدند. داده‌های خام جمع آوری شده توسط فرآیند دلفی- فازی ارزیابی و پردازش شد و در نهایت با استفاده از روش تصمیم‌گیری چند معیاره مورد تجزیه و تحلیل قرار گرفته و اولویت‌دهی شدند. معیارهای اولویت‌بندی شده به بهره‌برداران کمک می‌نماید تا نسبت به تهیه دستورالعمل و برنامه بازسازی معادن با در نظر گرفتن بودجه و بر اساس الزامات فعالیت‌های معدنی و محیط‌زیستی اقدام نموده و تصمیمات مفیدتر، مؤثرتر و کم هزینه‌تری را در این زمینه اتخاذ نمایند.

کلمات کلیدی: معیار بازسازی، متد تصمیم‌گیری، متد دلفی- فازی، بازسازی معدن.