

ORIGINAL RESEARCH PAPER

**COMPARATIVE ANALYSIS OF AHP AND FUZZY LOGIC
FOR CULTURAL LANDSCAPE-BASED EVALUATION OF
LAND-USE ALTERNATIVES: A CASE STUDY OF THE
KARTAL QUARRY AREA (ISTANBUL)**

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Abstract: This study aims to evaluate alternative land-use classes for the defunct Kartal Quarry in Istanbul within the scope of landscape restoration using cultural landscape criteria. A multi-criteria decision-making (MCDM) framework combining Analytical Hierarchy Process (AHP) and a fuzzy logic-based approach was employed, with expert judgment incorporated through consensus among three experts. The criteria were weighted using AHP, while the land-use alternatives were evaluated using a fuzzy logic-based approach to incorporate uncertainty. Recreational and Sports Areas ranked first in both approaches, followed by Healthcare Facilities and Residential Area. Statistical comparison using Spearman's rank correlation showed a very high level of agreement between the AHP and fuzzy Priority Rankings ($\rho = 0.9956, \rho < 0.001$), while sensitivity analysis indicated that the overall AHP Priority Ranking remained largely stable under $\pm 25\%$ and $\pm 50\%$ variations in criterion weights. The proposed framework provides a structured decision-support approach for cultural landscape-based land-use evaluation of defunct quarries under site-specific planning considerations.

Keywords: *cultural landscape, landscape restoration, land-use evaluation, multi-criteria decision-making, post-mining land use*

INTRODUCTION

Since the 1960s, with the commencement of planned development policies in Turkey, various decisions have been made to increase production. In this context, large investments have been made in the mining sector in particular, and the aim has been to utilize resources in the most efficient way. Especially in the use of quarries, the city of Istanbul has become a key hub for meeting raw material demands [1] (Figure 1). While there are universal rules for the proper closure and reintegration of mining sites into the city, decisions are largely made on a site-specific basis. In this process, site constraints, land-use potentials, and community needs are evaluated. Following mining activities, land degradation in the form of open pits, rock piles, topographical changes, and waste occurs. Due to these ecological and geophysical changes after mining, the surrounding landscape generally differs significantly from its pre-mining state [2]. Although the changes after mining are generally negative, they may offer potential for the creation of diverse landscape types. In the reconstruction of these areas, the primary goal should be to return the land to a safe and productive use, achieving the most harmonious integration of humans and nature [3]. In these areas, pit-type quarries can have landscape potential as water/wetland areas, water management areas, and ecological reserve areas; hillside quarries can highlight visual and cultural landscape functions; or lowland quarries can create large recreational areas [4].

The ecological, social, and economic evaluation of closed or abandoned mine sites is crucial for developing land management strategies and determining appropriate landscape restoration approaches. Land management strategies to be used in landscape restoration are listed as abandonment, remediation, restoration, reclamation, rehabilitation, repurposing, and co-purposing. In these areas, improvement measures should be implemented that eliminate factors that pose risks to human health or nature in the short or long term. Remediation is defined as the process of correcting the problem, ending or reversing its impact on human health or the environment. This process includes decontamination. Then, it should be evaluated whether it is possible to return the area to its former state. This is called the restoration process, which means returning the ecosystem and ecological balance to its previous state in terms of biodiversity, functionality, and structure. However, in many cases, this restoration is not possible due to the damage experienced. At this point, the land reclamation method is applied. In reclamation work, the ecosystem is replaced with other species that perform the same function [5].

The concept of landscape restoration refers to the rehabilitation, improvement, adaptive reuse, and long-term management of landscapes degraded by human activities or natural disasters. These processes aim to restore ecological functionality, enhance environmental quality, and introduce new uses where necessary, through the application of biological and technical methods in accordance with environmental, social, and economic conditions [6]. In landscape restoration, priority should be given to the creation of an environmentally friendly, stable and beneficial ecosystem. The developed landscape approach should support sustainable development and be able to meet biological production, cultural support and social service. Ecology, culture and economy are three interrelated and complementary sub-components of sustainable development. However, if these three components are considered together, the landscape value of an abandoned

quarry can be increased and sustainable development goals can be effectively achieved [7].

The landscape restoration process of degraded areas resulting from mining activities is typically carried out through the following steps [8]:

- (1) preliminary environmental assessment which reveals the current condition of the land and the nature of environmental risks;
- (2) planning the final post-mining use of the land;
- (3) conducting a detailed environmental assessment to characterize the nature and extent of adverse effects;
- (4) determining the most ideal methods for the disposal of pollutants;
- (5) developing a remediation work plan;
- (6) final management, maintenance and monitoring of the final condition.

The most important step in landscape restoration is determining the appropriate land use for the area. The primary challenge lies in the selection of appropriate variables to be considered when deciding on land use. Land affected by mining activities needs to be brought to a state where negative environmental, social and economic impacts are minimized and the end use that is beneficial to the community can be sustained. Here, it is necessary to make a beneficial land use decision with measurable reasons in terms of economic impacts, social justice and positive environmental impacts. Otherwise, it is evident that numerous alternatives exist for post-mining land uses. The decision leading to the selection of any alternative here should be based on sound engineering decisions aimed at improving the community and the environment, and on economic, environmental and social analyses [9].

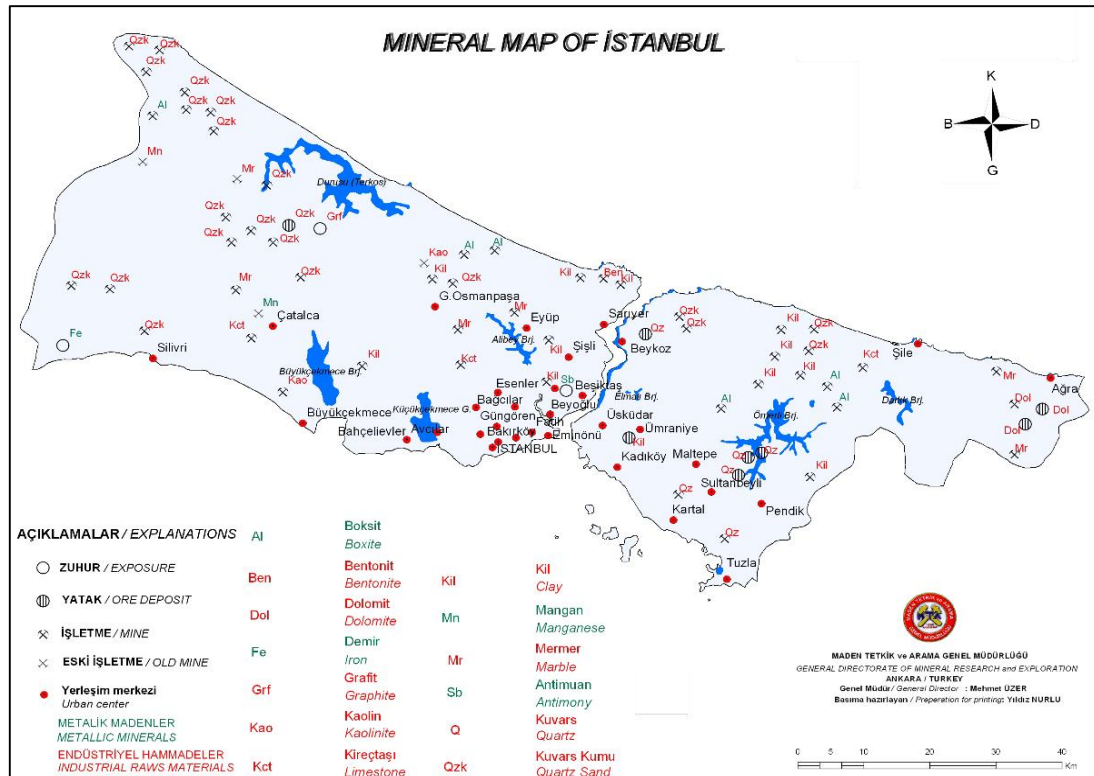


Figure 1. Istanbul Quarries, MTA, 2026 [10]

Since determining the land class alternative to be selected for the reintegration of quarries into the city requires the evaluation of numerous criteria and uncertainties, it is known that there are many studies in the literature using AHP and fuzzy logic-based integrated approaches. Some of these studies are presented. Kılıç *et al.* integrated fuzzy-AHP and GIS techniques to determine land suitability for wheat cultivation and produced suitability maps using topographic and soil characteristics as criteria. The results revealed that a large part of the area was unsuitable, while a limited part showed high suitability [11]. Pilevar *et al.* evaluated land suitability for wheat and maize in semi-arid regions using fuzzy-AHP and GIS. In the model created by considering climate, topography and soil factors, it was determined that a large part of the area was moderately suitable [12]. Bovkir *et al.* developed a fuzzy-AHP and GIS-based model for cargo locker site selection in Dublin. In the study where accessibility and infrastructure criteria stood out, the city center was determined as the most suitable area [13]. Ali *et al.* compared AHP and fuzzy models in landslide susceptibility analysis and showed that the fuzzy gamma model provided higher accuracy [14]. Sengupta *et al.* evaluated agricultural land suitability using FAHP and GIS and revealed that the fuzzy approach provided more reliable results by better representing uncertainties [15]. Tarife *et al.* analyzed site selection for renewable energy systems with fuzzy-AHP and GIS and showed that criteria based on energy potential were the most decisive factors [16].

However, although AHP and fuzzy-based MCDM approaches have been widely applied to different land-use and site-selection problems, the studies reviewed above have primarily focused on agricultural land suitability, infrastructure, landslide susceptibility, and renewable energy site selection. Comparatively limited attention has been given to the evaluation and prioritization of post-mining land-use alternatives based specifically on cultural landscape criteria, particularly in intensely urbanized quarry contexts. This represents a research gap that the present study seeks to address.

To address this gap, this study aims to examine the cultural landscape characteristics of the area surrounding the former Kartal Quarry in Istanbul and to evaluate and prioritize potential post-mining land-use alternatives for the area, which is under intense urban development pressure. To this end, site-specific cultural landscape criteria and potential land-use alternatives were identified and evaluated within a multi-criteria decision-making framework. The Analytic Hierarchy Process (AHP) was employed to determine the relative importance of the criteria and prioritize the alternatives, while a fuzzy logic-based approach was incorporated to account for the uncertainty and flexibility inherent in the decision-making process.

The primary contribution of the study lies not only in comparing the priorities derived from the AHP and fuzzy logic-based approaches, but also in examining the degree of agreement between the two methods using Spearman's rank correlation coefficient and analyzing the sensitivity of the rankings obtained through AHP to changes in criterion weights. In this way, the effects of different decision-making approaches and variations in criterion weights on land-use priorities are identified, with the aim of developing a more systematic assessment framework for the rehabilitation and adaptive reuse of abandoned quarries within a cultural landscape context.

Within this framework, the following research questions are addressed:

RQ1: How are the post-mining land-use alternatives for the Kartal Quarry prioritized according to the selected cultural landscape criteria?

RQ2: Considering uncertainty in the cultural landscape-based decision-making process, how do the AHP and fuzzy logic-based approaches differ in their evaluation and prioritization of alternative land uses?

RQ3: To what extent is the land-use priority ranking obtained through AHP consistent and robust with respect to changes in criterion weights?

The findings of the study are expected to contribute to the development of land-use and adaptive reuse strategies for the reintegration of abandoned quarries into the urban system. In this respect, the study provides a methodological framework for the adaptive reuse of abandoned quarries by integrating cultural landscape criteria, uncertainty, methodological agreement, and sensitivity analysis within a unified decision-making approach.

MATERIALS AND METHODS

Characteristics of the study area

This study focuses on the Kartal Quarry Area located on the Anatolian side of Istanbul, the location of which is shown in Figure 2. The study area, approximately 410,000 m² in size, encompassing parcels 12711/4, 12711/1, and 2796/366, has ceased to function as a quarry.



Figure 2. The Location of the Closed Kartal Quarry in Istanbul, 2009 [21]

Located on the side of the highway, in an old quarry about 65 meters deep, there is an artificial lake of 130,000 m². The lake, formed by the accumulation of rainwater, has become a habitat for various fish and bird species, creating an important natural life cycle within the city [17]. It is known that quartz stone mining, used as a raw material for cement, was carried out in the area where the pit mining method is used [4]. The spatial structure of the closed Kartal Quarry, showing its urban density, is presented in Figure 3.

Based on the studies of Pagouni *et al.* [5], Cındık Akıncı [6], Ramani *et al.* [18], and Akpınar [19], nine cultural landscape and planning-oriented criteria relevant to the evaluation of closed mining areas were identified. In addition, 14 land-use classes were considered based on the studies of Pagouni *et al.* [5], Mborah *et al.* [9], and Narrei and Osanloo [20]. The criteria and land-use classes were further reviewed through the expert evaluation procedure described below.

Two complementary methods, AHP and a fuzzy logic-based evaluation approach, were employed within the MCDM framework to evaluate and prioritize the land-use alternatives. The methods are described in detail below.

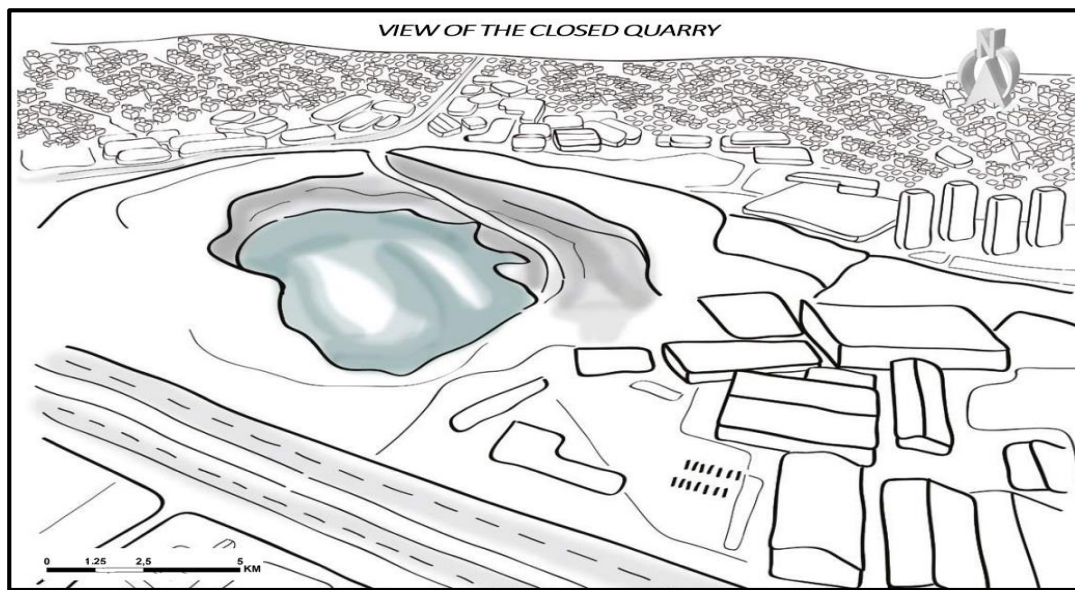


Figure 3. Sketch View of the Spatial Structure of the Closed Kartal Quarry [17]

Expert evaluation procedure

The expert evaluation process involved three experts with academic and professional expertise relevant to the scope of the study. The experts were selected based on their expertise in urban and regional planning, landscape architecture, cultural landscape, urban transformation, and land-use planning. Their professional backgrounds are summarized as follows:

Expert 1: Professor of Urban and Regional Planning with 40 years of professional experience and expertise in urban transformation and land-use planning.

Expert 2: Professor of Landscape Architecture with 34 years of professional experience and expertise in cultural landscape.

Expert 3: Landscape Architect with a doctoral degree and 19 years of professional experience, with expertise in cultural landscape.

The expert panel contributed to several stages of the evaluation process. First, the nine evaluation criteria were identified through a review of the relevant literature and subsequently reviewed and agreed upon jointly by the three experts. Similarly, the 14 land-use classes considered in the study were established based on the relevant literature and the joint assessment of the expert panel. The expert evaluations were conducted through online meetings. The experts then jointly evaluated each of the 14 land-use

classes according to each of the nine criteria using a 1 - 5 evaluation scale. For each criterion–alternative combination, the experts discussed their assessments and reached a consensus. The resulting 14×9 evaluation matrix represents a consensus-based expert evaluation rather than an aggregation of separate individual scores.

For the AHP analysis, the pairwise comparisons of the nine criteria were also conducted jointly by the three experts. Each criterion pair was discussed using Saaty's 1 – 9 scale, and a consensus was reached on its relative importance. Accordingly, a single consensus-based pairwise comparison matrix was constructed rather than separate matrices for individual experts. The resulting consensus-based criterion comparisons and alternative evaluation scores constituted the expert-derived inputs used in the subsequent AHP and fuzzy logic-based analyses.

The 1 - 5 scoring scale was used as a structured ordinal evaluation approach to translate expert judgments into comparable evaluation levels. The scores therefore represent consensus-based expert judgments rather than direct empirical measurements, with higher scores indicating a more favorable evaluation. In the AHP-weighted scoring procedure, these numerical scores were used as operational approximations of increasing evaluation levels to enable weighted aggregation with the AHP-derived criterion weights.

Method 1: Analytical hierarchy process (AHP)

In this study, AHP was used to determine the importance levels of the criteria within the scope of the MCDM problem. The method is based on the pairwise comparison approach developed by Thomas L. Saaty [22]. In the first stage, the problem was modeled within a hierarchical structure; the objective, criteria, and (if any) sub-criteria were defined. Then, the criteria were compared pairwise using Saaty's 1 – 9 importance scale. If necessary, intermediate values (2, 4, 6, 8) were also used to express the decision-maker's evaluations more precisely. The resulting pairwise comparison matrix was normalized and divided by the sum of each column, and the criterion weights were calculated by taking the row averages of the normalized matrix. The consistency of the comparisons was tested with the Consistency Ratio (CR). If the CR value was less than 0.10, the comparisons were considered consistent. In the final stage, the criteria were ranked according to their importance levels using the obtained weights. This process offers a systematic approach that quantitatively reveals the relative importance of the criteria in the decision-making problem. Figure 4 presents Saaty's pairwise comparison scale used in the AHP method and the Random Index (RI) values used in the consistency analysis. This structure provides a basic framework for determining the relative importance of the criteria and evaluating the consistency of the comparisons made. where CI is the Consistency Index, CR is the Consistency Ratio, and RI is the Random Index. This formulation is given in equations (1) and (2) [22].

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

$$CR = \frac{CI}{RI} \quad (2)$$

SAATY'S SCALE FOR PAIRWISE COMPARISON								
Numerical Value (x)	Verbal Evaluation		Explanation					
1	Equal importance		Two criteria contribute equally to the objective.					
3	Moderate importance of one over the other		Experience and judgment slightly favor one criterion over another.					
5	Strong importance of one over the other		Experience and judgment strongly favor one criterion over another.					
7	Very strong importance of one over the other		One criterion is very strongly favored over another; its dominance is demonstrated in practice.					
9	Extreme importance of one over the other		The evidence favoring one criterion over another is of the highest possible order.					
2, 4, 6, 8	Intermediate values		Used to represent compromise between two adjacent judgments.					
1/x (reciprocals of above values)	Inverse evaluation		If a criterion is assigned the value x when compared with a second criterion, then the second criterion has the reciprocal value 1/x when compared with the first.					

RANDOM INDEX (RI) VALUES (Saaty, 1977)								
Matrix Size (n)	3	4	5	6	7	8	9	10
Random Index (RI)	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Figure 4. Saaty's Scale and Random Index Values Used in AHP Pairwise Comparison [22]

Method 2: Fuzzy logic - based evaluation approach

In this study, the land use decision problem was modeled using a fuzzy logic approach in order to directly incorporate uncertainty and gradational evaluation into the analytical framework. Land use planning does not rely on strictly defined boundaries; both the relative importance of criteria and the performance of alternatives vary within ranges rather than fixed values. For this reason, all inputs were represented using triangular fuzzy numbers.

The dataset consists of two main components: the pairwise comparison matrix of criteria and the evaluation matrix of land use alternatives. Within the fuzzy framework, both components were transformed into a unified computational structure.

The pairwise comparison values were expressed as triangular fuzzy numbers as shown in equation (3) [23].

$$\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}) \quad (3)$$

This representation captures the lower, most probable, and upper bounds of each comparison. The fuzzy geometric mean for each criterion was calculated as shown in equation (4) [24]:

$$\tilde{r}_i = \left(\prod_{j=1}^n \tilde{a}_{ij} \right)^{1/n} \quad (4)$$

The fuzzy weights of the criteria were then obtained as shown in equation (5) [25]:

$$\tilde{w}_i = \tilde{r}_i \otimes (\sum_{i=1}^n \tilde{r}_i)^{-1} \quad (5)$$

These fuzzy weights were defuzzified using the centroid method as shown in equation (6) [23]:

$$w_i = \frac{l_i + m_i + u_i}{3} \quad (6)$$

For the evaluation of alternatives, the 1–5 scale scores assigned to each land use class were also converted into triangular fuzzy numbers as shown in equation (7) [23]:

$$\tilde{x}_{ik} = (l_{ik}, m_{ik}, u_{ik}) \quad (7)$$

The overall fuzzy evaluation value for each land use class was calculated as shown in equation (8) [26]:

$$\tilde{S}_k = \sum_{i=1}^n \tilde{w}_i \cdot \tilde{x}_{ik} \quad (8)$$

Finally, the fuzzy results were defuzzified to obtain comparable crisp scores as shown in equation (9) [23]:

$$S_k = \frac{l_k + m_k + u_k}{3} \quad (9)$$

This approach ensures that both uncertainty in criteria importance and variability in alternative evaluations are preserved throughout the decision-making process.

Statistical comparison of AHP and fuzzy priority rankings

To quantitatively compare the priority rankings of the land-use alternatives generated by the AHP and fuzzy approaches, a ranking-based comparative analysis was performed. The degree of agreement between the two priority rankings was examined using Spearman's rank correlation coefficient. In addition, NRC and MRS were used to determine the extent and magnitude of the observed differences in priority rankings.

First, Spearman's rank correlation coefficient was calculated to determine the degree of agreement between the rankings obtained from different prioritization methods. Spearman's rank correlation is a non-parametric statistical measure that evaluates the strength and direction of the association between two ranked variables. A coefficient approaching $\rho = 1$ indicates a strong positive correlation between the rankings, $\rho = 0$ indicates no correlation, and a coefficient approaching $\rho = -1$ indicates a strong negative correlation. Spearman's rank correlation coefficient was calculated using equation (10) [27].

$$\rho = 1 - \frac{6 \sum_{i=1}^n d_i^2}{n(n^2 - 1)} \quad (10)$$

In Equation (10), d_i represents the difference between the priority ranking positions of the same land-use alternative obtained from the AHP and fuzzy approaches, while n denotes the total number of land-use alternatives.

To quantify variations in the priority rankings, the priority shift (PS) of each land-use alternative was determined based on the difference between its ranking positions under the AHP and fuzzy approaches, as expressed in equation (11).

$$PS_i = R_{iB} - R_{iA} \quad (11)$$

In Equation (11), PS_i denotes the priority shift of the i th land-use alternative, while $R_{i,A}$ and $R_{i,B}$ represent its priority ranking positions under the two compared approaches, respectively. A non-zero PS_i value indicates a change in priority ranking, whereas $PS_i = 0$ indicates that the ranking remains unchanged.

Based on the calculated priority shift values, two summary indicators, NRC and MRS, were used to characterize the differences between the AHP and fuzzy priority rankings. NRC represents the total number of land-use alternatives whose priority ranking positions change between the two approaches, with a change identified when $PS_i \neq 0$. MRS represents the largest absolute priority shift observed across all land-use alternatives and is determined as the maximum value of $|PS_i|$. Together, these indicators quantify the extent and magnitude of the differences between the AHP and fuzzy priority rankings.

Sensitivity analysis

A one-at-a-time (OAT) sensitivity analysis was conducted to examine the effect of changes in criterion weights on the AHP priority rankings. Each of the nine criterion weights was independently varied by $\pm 25\%$ and $\pm 50\%$ relative to its baseline value. In each scenario, the weights of the remaining criteria were proportionally rescaled to maintain a total weight of 1. The AHP Scores of the 14 land-use alternatives were then recalculated, and the resulting Priority Rankings were compared with the baseline ranking. This analysis was used to identify whether changes in individual criterion weights affected the priority structure of the land-use alternatives and to determine which criteria had the greatest influence on the ranking results.

RESULTS AND DISCUSSION

This section presents the results obtained from the application of the AHP and fuzzy logic-based approaches. The findings are analyzed in terms of criteria weighting, alternative evaluation, and overall priority ranking.

Results of AHP - based evaluation

Figure 5 illustrates the hierarchical organization of the criteria used in the cultural landscape-based land-use evaluation. the framework includes zoning status, surrounding land use patterns, location, accessibility and infrastructure, demographic structure, landscape value, land size and shape, land ownership, and historical development.

A pairwise comparison matrix was constructed based on expert assessments to determine the relative importance of the cultural landscape criteria (Table 1). The results indicate that Zoning Status has the highest relative importance, whereas Historical Development has the lowest. The consistency ratio ($CR = 0.0352$) is below the accepted threshold of 0.10, indicating a high level of consistency in the expert judgments and supporting the use of the derived criterion weights in the evaluation.

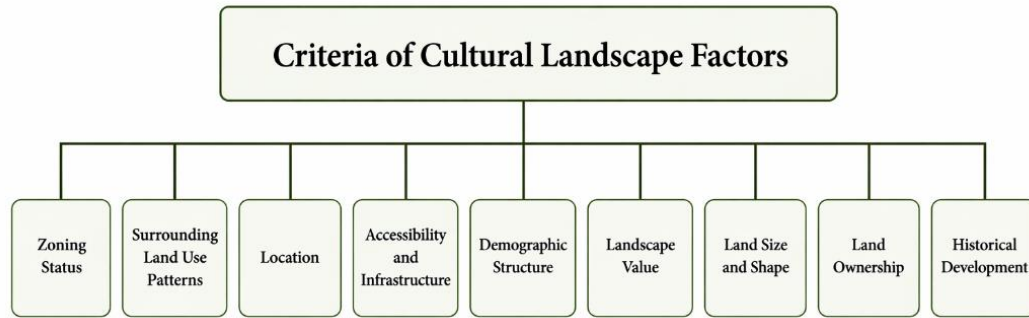


Figure 5. Hierarchical Structure of the Land Evaluation Criteria Used in Cultural Landscape Evaluation

Table 1. AHP pairwise comparison matrix of the evaluation criteria

Criterion	Zoning status	Surrounding land use patterns	Location	Accessibility and infrastructure	Demographic structure	Landscape value	Land size and shape	Land ownership	Historical development
Zoning status	1	2	3	4	5	6	7	8	9
Surrounding land use patterns	0.5	1	2	3	4	5	6	7	8
Location	0.3333	0.5	1	2	3	4	5	6	7
Accessibility & infrastructure	0.25	0.3333	0.5	1	2	3	4	5	6
Demographic structure	0.2	0.25	0.3333	0.5	1	2	3	4	5
Landscape value	0.1667	0.2	0.25	0.3333	0.5	1	2	3	4
Land size and shape	0.1429	0.1667	0.2	0.25	0.3333	0.5	1	2	3
Land ownership	0.1250	0.1429	0.1667	0.2	0.25	0.3333	0.5	1	2
Historical development	0.1111	0.1250	0.1429	0.1667	0.2	0.25	0.3333	0.5	1

Table 2 presents the evaluation scores of the land-use alternatives on a 1–5 scale according to the selected criteria.

These scores were combined with the AHP-derived criterion weights to calculate the AHP-Weighted Score and establish the Priority Ranking of each alternative. The AHP-Weighted Score for each land-use class was calculated using equation (12):

$$S_j = \sum_{i=1}^n w_i \cdot s_{ij} \quad (12)$$

- w_i , weight of the i -th criterion obtained by AHP
- s_{ij} , score of the j -th land use class for the i -th criterion (1–5)
- n , total number of criteria.

Table 2. Evaluation of land use classes based on criteria scores (1 – 5 Scale)

Land Use Classes	Zoning status	Surrounding land use patterns	Location	Accessibility and infrastructure	Demographic structure	Landscape value	Land size and shape	Land ownership	Historical development
Residential Area	4	4	5	5	5	3	3	3	2
Commercial Area	4	4	5	5	4	2	3	3	1
Educational Area	4	4	5	5	4	3	3	4	2
Cultural Facilities	4	4	4	4	4	5	3	4	4
Healthcare Facilities	4	5	5	5	3	3	3	4	1
Recreational&Sports Areas	4	5	4	4	4	5	4	4	5
Infrastructure	3	3	5	5	1	1	5	4	1
Industrial Area	3	2	2	2	3	1	2	3	1
Forest Area	1	2	1	1	1	5	4	3	4
Agricultural Area	1	1	1	1	1	2	4	2	2
Livestock Area	1	1	1	1	1	1	4	2	1
Water/Wetland Area	4	4	3	2	3	5	4	4	5
Waste and Storage Area	1	1	2	4	1	1	2	3	1
Energy Production Area	3	2	2	2	3	1	2	3	1

As shown in Table 3, Recreational and Sports Areas achieved the highest AHP-Weighted Score (4.2904), followed by Healthcare Facilities (4.2579), Residential Area (4.1855), Educational Area (4.1350), Commercial Area (4.0369), and Cultural Facilities (4.0163).

Table 3. Priority ranking of land use classes based on AHP-weighted scores

Land Use Classes	AHP-Weighted Score	Priority Ranking
Recreational and Sports Areas	4.2904	1
Healthcare Facilities	4.2579	2
Residential Area	4.1855	3
Educational Area	4.1350	4
Commercial Area	4.0369	5
Cultural Facilities	4.0163	6
Water/Wetland Area	3.6237	7
Transportation Infrastructure	3.3291	8
Industrial Area	2.3371	9
Energy Production Area	2.3371	10
Forest Area	1.6512	11
Waste and Storage Area	1.5699	12
Agricultural Area	1.2093	13
Livestock Area	1.1370	14

These results indicate that land uses associated with recreational, public, residential, educational, commercial, and cultural functions received relatively high priority within

the cultural landscape and planning-oriented evaluation framework. Water/Wetland Area (3.6237) and Transportation Infrastructure (3.3291) occupied intermediate positions in the Priority Ranking, while Industrial Area and Energy Production Area obtained identical lower scores (2.3371). Forest Area (1.6512), Waste and Storage Area (1.5699), Agricultural Area (1.2093), and Livestock Area (1.1370) received the lowest AHP-Weighted Scores. Overall, the AHP results indicate a clear prioritization of the evaluated land-use alternatives according to the cultural landscape and planning-oriented criteria considered in the study.

Results based on the fuzzy logic approach

The fuzzy logic-based evaluation results for the land-use alternatives are presented in Table 4.

Table 4. Fuzzy evaluation results for land-use classes

Land Use Class	Fuzzy Score (l, m, u)	Defuzzified Score	Priority Ranking
Recreational and Sports Areas	(1.9790, 4.2923, 8.3147)	4.8620	1
Healthcare Facilities	(1.9744, 4.2748, 7.9437)	4.7310	2
Residential Area	(1.9124, 4.1931, 8.0617)	4.7224	3
Educational Area	(1.8845, 4.1435, 8.1043)	4.7107	4
Cultural Facilities	(1.8129, 4.0158, 8.2531)	4.6939	5
Commercial Area	(1.8394, 4.0500, 7.9424)	4.6106	6
Water/Wetland Area	(1.5846, 3.6207, 7.5336)	4.2463	7
Transportation Infrastructure	(1.4849, 3.3396, 6.7151)	3.8465	8
Industrial Area	(0.8518, 2.3383, 5.5187)	2.9030	9
Energy Production Area	(0.8518, 2.3383, 5.5187)	2.9030	10
Forest Area	(0.7717, 1.6358, 4.3262)	2.2446	11
Waste and Storage Area	(0.7426, 1.5668, 4.3123)	2.2072	12
Agricultural Area	(0.6433, 1.1990, 3.6724)	1.8382	13
Livestock Area	(0.6433, 1.1302, 3.5531)	1.7755	14

The Defuzzified Scores ranged from 1.7755 to 4.8620, providing a differentiated Priority Ranking of the evaluated alternatives. Recreational and Sports Areas achieved the highest Defuzzified Score (4.8620) and ranked first, followed by Healthcare Facilities (4.7310) and Residential Area (4.7224). Educational Area, Cultural Facilities, and Commercial Area also received relatively high scores, ranging from 4.6106 to 4.7107. Water/Wetland Area (4.2463) and Transportation Infrastructure (3.8465) occupied intermediate positions in the ranking. Industrial Area and Energy Production Area obtained identical Defuzzified Scores (2.9030), reflecting their identical input evaluations. Forest Area (2.2446) and Waste and Storage Area (2.2072) ranked lower, while Agricultural Area (1.8382) and Livestock Area (1.7755) received the lowest scores.

Statistical comparison results of AHP and fuzzy priority rankings

The results obtained from the AHP-based evaluation and the fuzzy logic approach exhibit a high degree of consistency in terms of overall ranking patterns, while also revealing differences in the evaluation and differentiation of alternatives. In both methods, Recreational and Sports Areas, Healthcare Facilities, and Residential Area are consistently ranked as the top three alternatives, indicating a strong alignment in the identified priority structure. To quantitatively assess the consistency between the two rankings, Spearman's rank correlation analysis was performed. As shown in Table 5, a very strong and statistically significant positive correlation was obtained between the AHP and fuzzy rankings ($\rho = 0.9956, \rho < 0.001$). NRC was limited to 2, while MRS was only 1. The observed rank changes involved Commercial Area and Cultural Facilities, which exchanged adjacent positions between the two methods. These findings provide quantitative evidence of the high level of agreement between the AHP and fuzzy ranking results.

Table 5. Comparison of AHP and fuzzy priority rankings

Compared Rankings	ρ	NRC	MRS	Most Affected Class
AHP vs. Fuzzy	0.9956	2	1	Commercial Area; Cultural Facilities

Another key observation concerns the lower-ranked alternatives. Both methods place Industrial Area, Energy Production Area, Agricultural Area, and Livestock Area among the lower-priority alternatives. Industrial Area and Energy Production Area obtained identical scores and were therefore considered tied; the consecutive rank numbers presented in the tables are used only for presentation purposes and do not indicate a difference in priority between these two alternatives.

While both methods produced highly convergent Priority Rankings, the fuzzy approach preserves the inherent ambiguity in expert judgments and evaluation scores and allows more gradual differentiation among alternatives with similar performance. In contrast, the crisp structure of AHP provides sharper distinctions between alternatives. Thus, the two approaches provide complementary perspectives by combining a clear priority ranking with an uncertainty-sensitive evaluation of alternative performance.

Sensitivity analysis results

The sensitivity analysis examined the stability of the AHP priority rankings under independent $\pm 25\%$ and $\pm 50\%$ changes in each criterion weight. For each scenario, the resulting priority ranking was compared with the baseline model using Spearman's rank correlation coefficient, NRC, and MRS. The results obtained for the $\pm 25\%$ and $\pm 50\%$ weight variations are presented in Tables 6 and 7, respectively.

As shown in Table 6, the priority ranking remained unchanged in 13 of the 18 scenarios under the $\pm 25\%$ weight variations, with Spearman's $\rho = 1.0000$, NRC = 0, and MRS = 0. Ranking changes occurred in only five scenarios: Location (+25%), Location (−25%), Accessibility and Infrastructure (+25%), Accessibility and Infrastructure (−25%), and Landscape Value (+25%). In all scenarios involving a ranking change, Spearman's correlation remained very high ($\rho = 0.9956$), while only two alternatives changed positions (NRC = 2) and the maximum shift was limited to one rank (MRS = 1).

Table 6. Sensitivity analysis results for ± 25 % changes in criterion weights

Sensitivity Scenario	ρ	NRC	MRS
Zoning status (+25 %)	1	0	0
Zoning status (-25 %)	1	0	0
Surrounding land use patterns (+25 %)	1	0	0
Surrounding land use patterns (-25 %)	1	0	0
Location (+25 %)	0.9956	2	1
Location (-25 %)	0.9956	2	1
Accessibility and infrastructure (+25 %)	0.9956	2	1
Accessibility and infrastructure (-25 %)	0.9956	2	1
Demographic structure (+25 %)	1	0	0
Demographic structure (-25 %)	1	0	0
Landscape value (+25 %)	0.9956	2	1
Landscape value (-25 %)	1	0	0
Land size and shape (+25 %)	1	0	0
Land size and shape (-25 %)	1	0	0
Land ownership (+25 %)	1	0	0
Land ownership (-25 %)	1	0	0
Historical development (+25 %)	1	0	0
Historical development (-25 %)	1	0	0

The observed changes consisted exclusively of exchanges between adjacent alternatives. Recreational and Sports Areas and Healthcare Facilities exchanged the first two positions under Location (+25 %); Commercial Area and Cultural Facilities exchanged the fifth and sixth positions under Location (-25 %), Accessibility and Infrastructure (-25 %), and Landscape Value (+25 %); and Forest Area and Waste and Storage Area exchanged the eleventh and twelfth positions under Accessibility and Infrastructure (+25 %).

Under the ± 50 % weight variations, changes in the priority rankings became more pronounced than those observed under the ± 25 % scenarios (Table 7). Nevertheless, the overall ranking structure remained highly consistent with the baseline model, with Spearman's ρ ranging from 0.9824 to 1.0000 across all scenarios. No ranking changes were observed for Zoning Status (± 50 %), Surrounding Land Use Patterns (+50 %), Land Size and Shape (± 50 %), or Land Ownership (± 50 %), for which $\rho = 1.0000$, NRC = 0, and MRS = 0.

The largest change occurred when the weight of Surrounding Land Use Patterns was reduced by 50 %. In this scenario, Spearman's ρ decreased to 0.9824, NRC increased to 5, and MRS reached 2. Residential Area moved from third to first position, while Recreational and Sports Areas and Healthcare Facilities shifted from first to second and from second to third positions, respectively. Forest Area and Waste and Storage Area also exchanged the eleventh and twelfth positions. In all other scenarios in which ranking changes occurred, MRS was limited to one position, while Spearman's ρ remained between 0.9912 and 0.9956.

Table 7. Sensitivity analysis results for ± 50 % changes in criterion weights

Sensitivity Scenario	ρ	NRC	MRS
Zoning status (+50 %)	1	0	0
Zoning status (-50 %)	1	0	0
Surrounding land use patterns (+50 %)	1	0	0
Surrounding land use patterns (-50 %)	0.9824	5	2
Location (+50 %)	0.9912	4	1
Location (-50 %)	0.9956	2	1
Accessibility and infrastructure (+50 %)	0.9912	4	1
Accessibility and infrastructure (-50 %)	0.9956	2	1
Demographic structure (+50 %)	0.9956	2	1
Demographic structure (-50 %)	0.9956	2	1
Landscape value (+50 %)	0.9956	2	1
Landscape value (-50 %)	0.9912	4	1
Land size and shape (+50 %)	1	0	0
Land size and shape (-50 %)	1	0	0
Land ownership (+50 %)	1	0	0
Land ownership (-50 %)	1	0	0
Historical development (+50 %)	0.9956	2	1
Historical development (-50 %)	0.9956	2	1

Overall, the sensitivity analysis indicates that the AHP priority structure is generally stable under moderate changes in criterion weights and remains highly consistent even under larger perturbations. The ± 25 % scenarios resulted only in limited exchanges between adjacent alternatives, whereas the ± 50 % scenarios revealed greater sensitivity, particularly when the weight of Surrounding Land Use Patterns was substantially reduced. Location, Accessibility and Infrastructure, Demographic Structure, Landscape Value, and Historical Development also produced limited ranking changes under specific perturbations, but these changes were generally restricted to one position. In contrast, changes in Zoning Status, Land Size and Shape, and Land Ownership did not alter the priority ranking even at the ± 50 % level. These findings indicate that the overall priority structure is not highly dependent on moderate variations in any single criterion weight, while also identifying the criteria and directions of change to which the ranking is comparatively more sensitive. Therefore, the findings support the overall stability of the ranking structure rather than implying complete invariance to changes in criterion weights.

Discussion

The findings of the present study were discussed in relation to previous research on post-mining land-use planning and abandoned quarry rehabilitation. Particular attention was given to the relative priorities of alternative land uses, the criteria considered in post-mining decision-making, and documented rehabilitation approaches. Although the study

areas, evaluation criteria, and methodological approaches differ across the studies, these comparisons provide relevant reference points for interpreting the present findings within a broader post-mining planning context.

Recent empirical evidence provides a useful reference for interpreting the relative priorities obtained in the present study. Brisudová and Frantál [28] reported mean preference values of 3.92 for natural succession, 3.79 for planned greenery, 3.32 for recreation and tourism, 2.35 for renewable energy production, and 2.29 for housing development based on local stakeholder evaluations of post-mining land-use alternatives. Although these values are not directly comparable with the AHP-Weighted Scores obtained in the present study because they were derived using different evaluation procedures, the relative preference patterns provide a useful real-world reference. In particular, recreation received relatively high priority in both studies, which is consistent with the first-place Priority Ranking of Recreational and Sports Areas for the Kartal Quarry. Differences were also observed, particularly for residential, energy-related, and nature-oriented uses, indicating that post-mining land-use priorities remain dependent on site-specific spatial, social, and planning conditions.

Simpson *et al.* [29] emphasized that post-mining land-use selection should be informed by a comprehensive knowledge base incorporating regulatory requirements, land capability, environmental baseline conditions, and land ownership considerations. These dimensions are particularly relevant to the Zoning Status, Landscape Value, and Land Ownership criteria considered in the present AHP framework. The authors also highlighted the use of GIS, MCDM, and fuzzy logic as relevant tools for supporting PMLU selection. In the Australian context, documented PMLU options include native ecosystems, habitat, ecosystem services, grazing, landfill, water storage, infrastructure, and renewable energy uses. These options correspond to several land-use classes evaluated in the present study, particularly Forest Area, Livestock Area, Waste and Storage Area, Water/Wetland Area, Infrastructure, and Energy Production Area. Moreover, documented redevelopment cases in New South Wales demonstrate that former mining and industrial sites can also undergo residential and retail redevelopment following appropriate remediation. Although the regulatory and spatial contexts differ from that of the Kartal Quarry, these documented planning approaches and post-mining uses provide contextual support for the criteria and range of land-use alternatives considered in the present framework.

Tsolaki-Fiaka *et al.* [30] provide a more direct comparison in the context of abandoned quarry rehabilitation. The authors evaluated alternative restoration scenarios for two abandoned quarries in Greece using a multi-criteria decision analysis approach based on financial, environmental, and socioeconomic criteria. For the Mikro Derio quarry, when greater weight was assigned to socioeconomic criteria, the preferred scenario combined quarry restoration with a wildlife observatory and areas for recreation and alternative forms of tourism. This finding is consistent with the high priority assigned to recreational functions in the present study, where Recreational and Sports Areas achieved the highest AHP-Weighted Score and ranked first among the evaluated land-use alternatives. This comparison provides contextual support for the practical relevance of recreational functions as a potential post-quarry land-use option, while recognizing that preferred rehabilitation alternatives remain dependent on site-specific conditions and the criteria considered.

Limitations and future research

The present study has several limitations that should be considered when interpreting the results. The proposed framework primarily focuses on cultural landscape criteria and therefore does not constitute a comprehensive ecological assessment of post-mining landscape restoration. Ecological dimensions such as flora, fauna, habitat suitability, ecological connectivity and corridors, and ecosystem services were not explicitly incorporated into the current decision model. Their exclusion may limit the ability of the framework to capture the full ecological complexity of post-mining restoration decisions. Future research could extend the proposed framework by integrating these dimensions as an additional ecological assessment layer and examining their influence on land-use priorities.

In addition, the present study does not explicitly incorporate natural landscape data such as slope, aspect, elevation, geology, and hydrology. These variables represent important components of the natural landscape and can provide additional information on the physical and environmental characteristics of a site. Future research could integrate these natural landscape data together with ecological dimensions into the cultural landscape-based framework, enabling a broader assessment of post-mining land-use alternatives.

CONCLUSIONS

This study presented an integrated multi-criteria decision-support framework for the cultural landscape-based evaluation of land-use alternatives in the Kartal Quarry Area on the Anatolian side of Istanbul. By combining AHP and a fuzzy logic-based approach, the framework enabled the systematic evaluation and prioritization of alternative land uses based on selected cultural landscape criteria. Recreational and Sports Areas ranked first in both approaches, followed by Healthcare Facilities and Residential Area, indicating a consistent priority structure among the highest-ranked alternatives. Considering the urban context of the Kartal district in Istanbul, the high priority assigned to recreational uses is consistent with the need for green spaces in the area. At the same time, the third-highest priority assigned to Residential Area reflects the development pressure associated with ongoing urbanization in the surrounding area.

The statistical comparison confirmed a very high level of agreement between the AHP and fuzzy Priority Rankings, with only limited changes in rank positions. In addition, the sensitivity analysis showed that the overall AHP Priority Ranking remained largely stable under independent $\pm 25\%$ and $\pm 50\%$ variations in criterion weights, although some alternatives changed positions under specific scenarios. These findings demonstrate that the resulting priority structure is generally stable while also identifying where changes in criterion importance may influence the ranking.

From a decision-support perspective, the study contributes a structured framework that combines criterion weighting, alternative evaluation, quantitative comparison of ranking agreement, and sensitivity analysis within a common assessment process. This framework provides a transparent basis for interpreting land-use priorities rather than defining a universally optimal land use. In metropolitan areas such as Istanbul, where abandoned quarry sites may present opportunities for redevelopment, such an approach can assist

planners and decision-makers in systematically evaluating alternative uses based on site-specific cultural landscape criteria.

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