Selection of plant location in the natural stone industry using the fuzzy multiple attribute decision making method

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Synopsis

Determining the most convenient plant location is one of the most commonly encountered problems in engineering applications. This paper presents a fuzzy multiple attribute decision making (FMADM) model which is developed for the selection of the optimum plant location for natural stone factories in the mining industry. The criteria affecting the decision making process in natural stone industry were determined to solve the plant location problem in the FMADM model. To determine the optimum plant location for a new natural stone factory, which is planned to be established by a mining firm located in the Eskisehir region of Turkey, an analysis was carried out by incorporating the method and the analytic hierarchy process (AHP) method. The analysis shows that the Yager's method can easily be applied to the selection of plant location in the natural stone and mining industry when the difficulties encountered in the application process of the AHP method is taken into account.

Keywords: Natural stone, plant location, decision making, Yager's method, analytic hierarchy process (AHP).

Introduction

For all branches of engineering, selection of plant location is a common concern and crucial to all companies' eventual success. Selecting a plant location is very important for all companies in minimizing cost and maximizing the use of resources. The new plant location should be evaluated carefully for the company's competitiveness. To achieve this goal, some potential criteria must be considered in selecting a particular plant location, such as investment cost, human resources, availability of the material, climate, etc. All the criteria affecting the optimum plant location selection can be classified into two categories as subjective and objective. Subjective criteria are qualitatively defined as climate, manpower, etc. while objective criteria are quantitatively defined as land and installation cost.

Multiple criteria decision making (MCDM) is one of the most considerable branches of decision-making. MCDM refers to making decisions in the presence of multiple, usually conflicting, criteria. The problems in MCDM are classified into two categories: multiple attribute decision making (MADM) and multiple objective decision making (MODM). However, very often the terms MADM and MCDM are used to mean the same class of models and mostly confused in practice. Usually, MADM is used when the model cannot be stated in mathematical equations and otherwise MODM is used. Therefore, determining the plant location is a MCDM problem but this kind of problem is mostly categorized in MADM so that the decision maker can evaluate the subjective criteria in the problem. The decision maker wants to maximize more than one objective criterion for the selection of plant location stage. Among the plant location alternatives, the most suitable plant location must be selected according to objectives and alternatives. MADM applications can help the decision maker to reach the optimal solution for the selection of the plant location. In the natural stone industry, MADM methods can be applied to the selection of plant location because it is a process that includes subjective and objective criteria affecting the selection of plant location among the alternatives.

Turkey's income from natural stone exports reached to a total of $626 million in 2004. It is constituted around 53% of the Turkey's total mining export income in that year[1]. Natural stone exports reached to total of $808 million in 2005 and exceeded $1 billion in 2006[2]. In 2007, natural stone exports will increase to $1.2 billion and 80% of the country's total mining exports. The natural stone production rate of Turkey was increased by 35% between 2000 and 2004. In 2004, 9% of the world's natural stone production came from Turkey[1]. In the future, it is expected that the Turkish natural stone industry's production rate will increase and new natural

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stone factories will be constructed in different regions of Turkey. The most suitable location must be selected to achieve the planned production target in natural stone industry. To solve this problem, fuzzy multiple attribute decision making (FMADM), that is the MADM technique, was used in this study and an FMADM model was developed to help the decision maker working in natural stone processing. In the developed model, an expert team determined all the criteria affecting the plant location of the natural stone industry and weighted the pairwise comparison matrices at the first stage of the problem solving process. The FMADM, since its invention, has been a tool in the hands of decision makers and researchers; and it is one of the most commonly used MADM tools. The FMADM method has been increasingly incorporated in mining applications such as roadheader selection[3], selection of post-mining usage of land[4], open pit mine equipment selection[5], underground mining method selection[6,7] and the selection of loading-hauling system in an open pit mine[8]. In this paper, an analysis was carried out by employing the FMADM method in order to determine the optimum plant location for a new natural stone factory, which is planned to be established by a mining firm in Turkey. Also, an analytic hierarchy process (AHP) method was applied to solve the same problem for comparison of the solutions.

Fuzzy multiple attribute decision making method

Fuzzy multiple attribute decision making (FMADM) methods have been developed due to the lack of precision in assessing the relative importance of attributes and the performance ratings of alternatives for an attribute. The imprecision may come from a variety of sources such as: unquantifiable information, incomplete information, nonobtainable information and partial ignorance. The classic MADM methods cannot effectively handle the problems with such imprecise information[9].

The problem of fuzzy MADM is to select/prioritize/rank a finite number of courses of action (or alternatives) by evaluating a group of predetermined criteria. Thus, to solve this problem, an evaluation procedure to rate and rank, in order of preference, the set of alternatives must be constructed. The fuzzy MADM problem is described below[9]:

- A set of m possible courses of action (referred to as alternatives), $A = \{A_1, A_2, \ldots, A_i, \ldots, A_m\}$
- A set of n attributes (or criteria), $C = \{C_1, C_2, \ldots, C_j, \ldots, C_n\}$ with which alternative performances are measured
- A performance rating of alternative A_i with respect to attribute (or criterion) C_j, which is given by the $m \times n$ fuzzy decision matrix $\check{R} = \{\check{R}_{ij} \mid i = 1, 2, \ldots, m; j = 1, 2, \ldots, n\}$, where $\check{R}_{ij}$ is a fuzzy set (or fuzzy number); and
- A set of n fuzzy weights $\hat{W} = \{\hat{W}_j \mid j = 1, 2, \ldots, n\}$, where $\hat{W}_j$ is also a fuzzy set (or fuzzy number) and denotes the importance of criterion j, C_j, in the evaluation of the alternatives.

A large number of articles in the literature on decision-making analysis have addressed to the FMADM methods. The focus of this paper is on the Yager's method, which is generally enough to deal with multiple attribute problems. Yager's method[10] follows the max-min method of Bellman and Zadeh[11], with the improvement of Saaty's method[12], which considers the use of a reciprocal matrix to express the pairwise comparison criteria and the resulting eigenvector as subjective weights (priorities). The weighting procedure uses exponentials based on the definition of linguistic hedges, proposed by Zadeh[13].

On describing multiple attribute decision-making problems, only a single objective is considered, namely the selection of the best alternative from a set of alternatives. The decision method assumes the max-min principle approach. The fuzzy set decision is the intersection of all criteria[14]:

$$\mu_D(A) = \min\left[\mu_{C_1}(A), \mu_{C_2}(A), \ldots, \mu_{C_n}(A)\right] \quad [1]$$

for all $A_i \in A$, and the optimal decision is yielded by,

$$\mu_D(A^*) = \max_{A} \mu_D(A) \quad [2]$$

where A^* is the optimal decision and μ is membership degrees of alternatives for each criterion.

A main difference in this approach is that the importance of criteria is represented as exponential scalars. This is based on the idea of linguistic hedges. The rationale behind using weights (or importance levels) as exponents is that the higher the importance of criteria, the larger should be the exponent, giving the minimum rule. Conversely, the less important a criterion, is the smaller its weight. This seems intuitive. Formally:

$$\mu_D(A) = \min\left\{\begin{matrix}\left[\mu_{C_1}(A)\right]^{\alpha_1}, \left[\mu_{C_2}(A)\right]^{\alpha_2} \\ \ldots, \left[\mu_{C_n}(A)\right]^{\alpha_n}\end{matrix}\right\} \quad [3]$$

where α is weight of the criteria (for $\alpha > 0$).

Yager[10] suggests the use of Saaty's method[12] for pairwise comparison of the criteria (attributes). A pair-wise comparison of criteria (attributes) could improve and facilitate the assessment of criteria importance. Yager suggests that, for a decision problem, the use of the resulting eigenvector expresses a decision maker's empirical estimation of the level of importance of alternatives for a given criterion[8].

General information about the analysed company

ELMAS natural stone factories are one of the most important groups of Turkey's travertine industries. They have their own travertine quarries and two factories. The first ELMAS natural stone factory was founded in 1986, and they have been supplying the raw material from their own travertine quarry in Denizli for 21 years, so far. In 1997, the second natural stone factory was established in Eskisehir, which is located in the northwestern part of Turkey (Figure 1). After a travertine block produced from the travertine quarry in Denizli, the block is transported to the natural stone processing factory either in Denizli or Eskisehir. The travertine blocks can either go to a gang saw machine or to a block cutting machine. In the Denizli factory, travertine blocks are cut only as a strip and rough draft slabs (Figure 2). The strips and rough draft slabs are transported to the factory in Eskisehir to be processed as polished travertine slabs. In the Eskisehir factory, travertine strips and rough draft slabs are processed in a sequence of calibrating, wax

Figure 1—The location of ELMAS natural stone factories in Turkey

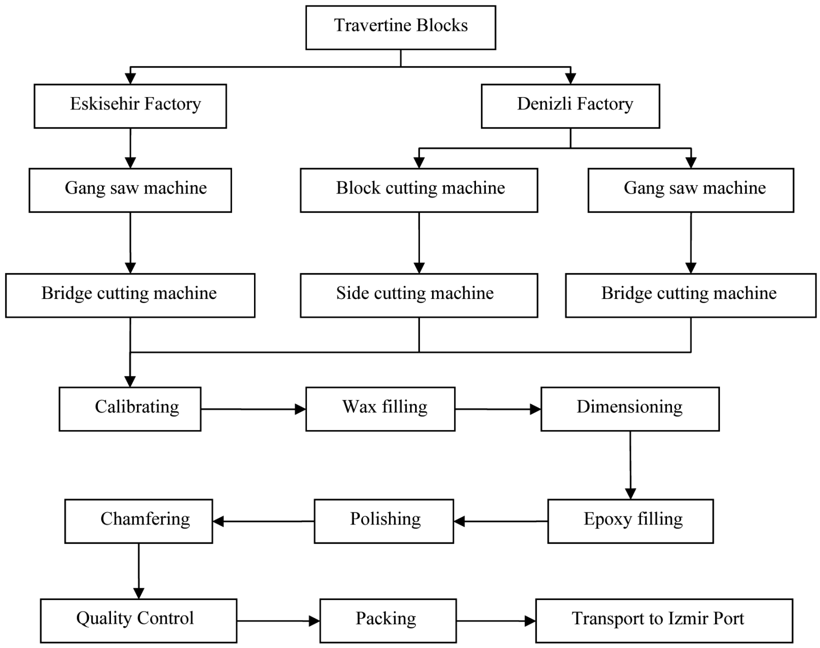

Figure 2—ELMAS natural stone factories' production lines

filling, dimensioning, polishing, chamfering, quality controlling and packing operations (Figure 2). Finally the terminal products are transported to Izmir port to be exported. The firm management has decided to establish a new natural stone factory in 2008. The four alternative plant locations are determined by the management as follows: Eskisehir-Muttalip, Bozuyuk, Afyon-Iscehisar and Denizli district. The four facility alternatives, the location of travertine quarry and two present factories can be seen in the map (Figure 1).

Application of FMADM to determine the location of new ELMAS natural stone factory

The criteria and sub-criteria assessed by an expert team consisting of one geology engineer, who is the manager of the firm and has 20 years of experience in the natural stone industry, two mining engineers, who have 10 years of experience in the natural stone industry, and one firm owner, who has 40 years of experience in the natural stone industry. All decisions have a common hierarchical structure whereby options are evaluated against the various criteria that promote the ultimate decision objective. The most convenient problem of the new natural stone factory plant location selection was structured in a hierarchy of different levels, as shown in Figure 3[15]. The number of criteria and alternatives should be considered by the pairwise comparison matrix applications because of the consistency and validity of the decision-making process as stated by some researchers[16,17]. The number of alternatives should be 7±2, otherwise the grouping method should be applied[18–20].

After structuring a hierarchy, the pairwise comparison matrix was constructed for each level. During the pairwise consideration, a nominal scale, given in Table I[12], was used for the evaluation. Each main criterion affecting plant location selection was compared with the others and the pairwise comparison matrix of main criteria was constructed and is given in Table II. In constructing pairwise comparison matrices, every expert team member constructed his own matrices. And, the final form of each pairwise comparison matrices was obtained, by averaging and rounding the values, assigned by each member.

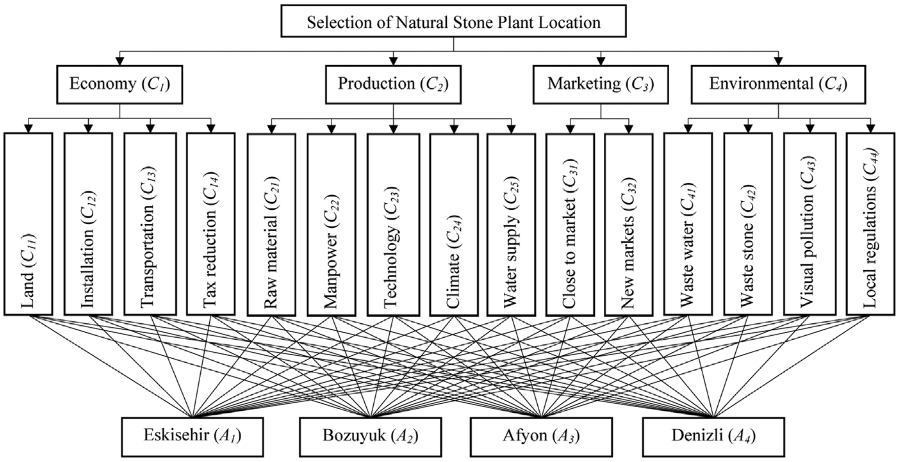

Figure 3—Hierarchy structure for selection of natural stone factory location[15]

Table I

Scale for pairwise comparisons[12]

Relative intensity definition	
1	Of equal value
3	Slightly more value
5	Essential or strong value
7	Very strong value
9	Extreme value
2,4,6,8	Intermediate values

Table II

Pairwise comparison matrix of main criteria

Main criteria	C_1	C_2	C_3	C_4	Eigen values
Economy (C_1)	**1**	3	7	5	0.581
Production (C_2)	1/3	**1**	4	3	0.257
Marketing (C_3)	1/7	1/4	**1**	2	0.094
Environmental (C_4)	1/5	1/3	1/2	**1**	0.068

$\lambda_{max} = 4.081$, $CR = 0.030 \leq 0.1$; OK

After performing the comparison, the maximum eigen value (λ_{max}), consistency index (CI) and consistency ratio (CR) were found to perform pairwise comparison's consistency[12].

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n}\left\{\frac{\sum_{j=1}^{n} a_{ij} \times w_j}{w_i}\right\} \quad [4]$$

where λ_{max} is the maximal or principal eigen value, and n is the matrix size, a_{ij} is an element of pairwise comparison matrix, w_j and w_i is the jth and ith element of eigen values, respectively.

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad [5]$$

$$CR = \frac{CI}{RI} \quad [6]$$

where RI is the random indices.

To find out whether the resulting consistency index is acceptable, the consistency ratio should be calculated. The consistency indices of randomly generated reciprocal matrices from the scale 1 to 9 are called the random indices, RI. The ratio of consistency index to RI for the same-order matrix is called the consistency ratio, CR. Random indices are given in Table III[12].

As a general rule, a consistency ratio of 0.10 or less is considered acceptable. This means that the result here is less than ideal. In practice, however, consistency ratios exceeding 0.10 occur frequently.

As shown in Table II, the economy criterion is the most important factor (eigen value or priority 0.581) and it is followed by the production criterion. The mean λ_{max} value is 4.081 which is near the matrix size and the CR value is 0.030 which is less than 0.1. The pairwise comparison is acceptable and there is no need to make new comparisons again.

After constructing the pairwise comparison matrix of main criteria, all the subgroups of each main criterion should be compared with the others as shown in Table IV, V, VI and VII.

The respective weights of sub-criteria were finally obtained from the eigenvector of the matrix as shown in Table VIII. The total eigen values for each sub-criterion were

Table III

The consistency indices of randomly generated reciprocal matrices[12]

	Order of the matrix												
	1,2	3	4	5	6	7	8	9	10*	11*	12*	13*	14*	15*
RI	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

* For validation, consistency and redundancy, the best number of criteria should be 7±2[16,17]

calculated by multiplying the eigen value of its sub-criterion given in Table IV (0.112 for Land sub-criterion) with the eigen value of the main criteria given in Table II (0.581).

The eigenvector corresponds to the weights to be associated with the memberships of each criterion. The exponential weighting was consequently defined for each criterion as: α_1=0.065, α_2=0.044, α_3=0.33, α_4=0.141, α_5=0.107, α_6=0.068, α_7=0.041, α_8=0.025, α_9=0.016, α_{10}=0.063, α_{11}=0.031, α_{12}=0.004, α_{13}=0.011, α_{14}=0.046 and α_{15}=0.006.

The set of possible plant location alternatives is A = {Eskisehir-Muttalip (A_1), Bozuyuk (A_2), Afyon-İscehisar (A_3), Denizli (A_4)} and C = {C_{11}, C_{12}, C_{13}, C_{14}, C_{21}, C_{22}, C_{23}, C_{24}, C_{25}, C_{31}, C_{32}, C_{41}, C_{42}, C_{43}, C_{44}} is the set of selection criteria. A decision maker is asked to define the membership levels of each criterion after conferring with experts on this subject according to the Figure 4[9].

Table IV

Pairwise comparison matrix for the economy criterion and its sub-criteria

Economy criterion (C_1)	C_{11}	C_{12}	C_{13}	C_{14}	Eigen values
Land (C_{11})	**1**	2	1/5	1/3	0.112
Installation (C_{12})	1/2	**1**	1/9	1/2	0.075
Transportation (C_{13})	5	9	**1**	2	0.569
Tax reduction (C_{14})	3	2	1/2	**1**	0.243

λ_{max} = 4.121, CR = 0.045 ≤ 0.1; OK

Table V

Pairwise comparison matrix for production criterion and its subcriteria

Production criterion (C_2)	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	Eigen values
Raw material (C_{21})	**1**	2	3	4	5	0.417
Manpower (C_{22})	1/2	**1**	2	3	4	0.263
Technology (C_{23})	1/3	1/2	**1**	2	3	0.160
Climate (C_{24})	1/4	1/3	1/2	**1**	2	0.097
Water supply (C_{25})	1/5	1/4	1/3	1/2	**1**	0.062

λ_{max} = 5.068, CR = 0.015 ≤ 0.1; OK

Table VI

Pairwise comparison matrix for marketing criterion and its subcriteria

Marketing criterion (C_3)	C_{31}	C_{32}	Eigen values
Close to market (C_{31})	**1**	2	0.667
New markets (C_{32})	1/2	**1**	0.333

λ_{max} = 2, CR = 0 ≤ 0.1; OK

Table VII

Pairwise comparison matrix for environmental criterion and its subcriterion

Environmental criterion (C_4)	C_{41}	C_{42}	C_{43}	C_{44}	Eigen values
Waste water (C_{41})	1	1/3	1/7	1/2	0.063
Waste stone (C_{42})	3	1	1/5	2	0.168
Visual pollution (C_{43})	7	5	1	9	0.676
Local regulations (C_{44})	2	1/2	1/9	1	0.093

λ_{max} = 4.099, CR = 0.037 ≤ 0.1; OK

Table VIII

Calculation of total eigen value for each sub-criterion

Definition Main criterion (Main)	Sub-criterion (Sub)	Eigen values of criteria Sub	Main	Total
Economy (C_1)	Land (C_{11})	0.112	0.581	0.065
	Installation (C_{12})	0.075		0.044
	Transportation (C_{13})	0.569		0.33
	Tax reduction (C_{14})	0.243		0.141
Production (C_2)	Raw material (C_{21})	0.417	0.257	0.107
	Manpower (C_{22})	0.263		0.068
	Technology (C_{23})	0.160		0.041
	Climate (C_{24})	0.097		0.025
	Water supply (C_{25})	0.062		0.016
Marketing (C_3)	Close to market (C_{31})	0.667	0.094	0.063
	New markets (C_{32})	0.333		0.031
Environmental (C_4)	Waste water (C_{41})	0.063	0.068	0.004
	Waste stone (C_{42})	0.168		0.011
	Visual pollution (C_{43})	0.676		0.046
	Local regulations (C_{44})	0.093		0.006

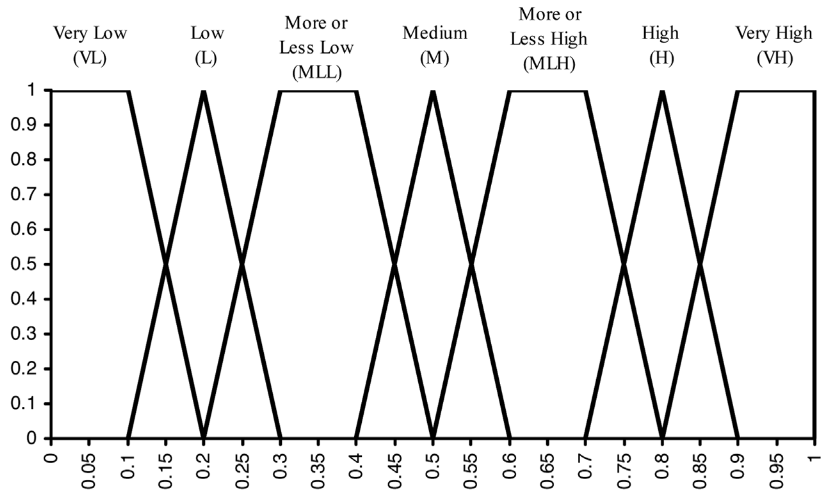

Figure 4—Linguistic model for fuzzy numbers

Table IX

ML of each criterion by using linguistic assessments and MDF of each criterion by the Yager's Method

Criterion	Alternatives											
	Eskisehir-Muttalip (A_1)			Bozuyuk (A_2)			Afyon-Iscehisar (A_3)			Denizli (A_4)		
	ML		MDF	ML		MDF	ML		MDF	ML		MDF
C_{11}	L	0.20	0.901	VH	0.95	0.997	MLL	0.35	0.934	MLL	0.35	0.934
C_{12}	MLL	0.35	0.955	H	0.80	0.990	M	0.50	0.970	VL	0.05	0.877
C_{13}	L	0.20	0.587	MLL	0.35	0.707	M	0.50	0.795	VH	0.95	0.983
C_{14}	VL	0.05	0.655	VH	0.95	0.993	MLH	0.65	0.941	MLL	0.35	0.862
C_{21}	L	0.20	0.842	MLL	0.35	0.894	MLH	0.65	0.955	VH	0.95	0.995
C_{22}	L	0.20	0.897	VH	0.95	0.997	M	0.50	0.954	VL	0.05	0.817
C_{23}	L	0.20	0.936	VH	0.95	0.998	M	0.50	0.972	VL	0.05	0.884
C_{24}	L	0.20	0.961	MLL	0.35	0.974	L	0.20	0.961	H	0.80	0.994
C_{25}	MLL	0.35	0.984	M	0.50	0.989	L	0.20	0.975	VH	0.95	0.999
C_{31}	H	0.80	0.986	MLH	0.65	0.973	MLL	0.35	0.936	H	0.80	0.986
C_{32}	MLL	0.35	0.968	VH	0.95	0.998	M	0.50	0.979	L	0.20	0.951
C_{41}	MLL	0.35	0.995	M	0.50	0.997	VH	0.95	0.999	L	0.20	0.993
C_{42}	VL	0.05	0.966	M	0.50	0.992	MLH	0.65	0.995	H	0.80	0.997
C_{43}	M	0.50	0.969	L	0.20	0.928	VH	0.95	0.998	VL	0.05	0.871
C_{44}	MLL	0.35	0.993	H	0.80	0.999	MLH	0.65	0.997	VL	0.05	0.981

Table IX shows the membership levels (ML) assigned by the expert team for each criterion (VH: Very High, H: High, MLH: More or Less High, M: Medium, MLL: More or Less Low, L: Low, VL: Very Low). The membership decision function (MDF) according to Yager[10] was determined for each alternative and they are also given in Table IX.

Using membership degrees of alternatives for each criterion and weights of the criteria, the following results were obtained for each alternative according to Equation [3]:

- ➤ $\mu_D(A_1)=\min(0.20^{0.065}, 0.35^{0.044}, 0.20^{0.331}, 0.05^{0.141}, 0.20^{0.107}, 0.20^{0.068}, 0.20^{0.041}, 0.20^{0.025}, 0.35^{0.016}, 0.80^{0.063}, 0.35^{0.031}, 0.35^{0.004}, 0.05^{0.011}, 0.50^{0.046}, 0.35^{0.006})=0.587$
- ➤ $\mu_D(A_2)=\min(0.95^{0.065}, 0.80^{0.044}, 0.35^{0.331}, 0.95^{0.141}, 0.35^{0.107}, 0.95^{0.068}, 0.95^{0.041}, 0.35^{0.025}, 0.50^{0.016}, 0.65^{0.063}, 0.95^{0.031}, 0.50^{0.004}, 0.50^{0.011}, 0.20^{0.046}, 0.80^{0.006})=0.707$
- ➤ $\mu_D(A_3)=\min(0.35^{0.065}, 0.50^{0.044}, 0.50^{0.331}, 0.65^{0.141}, 0.65^{0.107}, 0.50^{0.068}, 0.50^{0.041}, 0.20^{0.025}, 0.20^{0.016}, 0.35^{0.063}, 0.50^{0.031}, 0.95^{0.004}, 0.65^{0.011}, 0.95^{0.046}, 0.65^{0.006})=0.795$
- ➤ $\mu_D(A_4)=\min(0.35^{0.065}, 0.05^{0.044}, 0.95^{0.331}, 0.35^{0.141}, 0.95^{0.107}, 0.05^{0.068}, 0.05^{0.041}, 0.80^{0.025}, 0.95^{0.016}, 0.80^{0.063}, 0.20^{0.031}, 0.20^{0.004}, 0.80^{0.011}, 0.05^{0.046}, 0.05^{0.006})=0.862$.

Using the max-min Bellman and Zadeh principle, the final set was determined as below yielding the result:

$\mu_D(A)$=(Eskisehir-Muttalip (A_1)/0.587, Bozuyuk (A_2)/0.707, Afyon-Iscehisar (A_3)/0.795, Denizli (A_4)/0.862)

and the optimal solution is: μ_D (A^*) max ($\mu_D(A_4)$) 0.862.

In conclusion, the Denizli (A_4) alternative resulted as the most suitable natural stone plant location with the membership degree of 0.862 when the membership degrees of the other alternatives were compared.

Sensitivity analysis

In order to improve the quality of the results, a sensitivity analysis was performed on the final outcome. Sensitivity analysis is concerned with 'what kind of question should be asekd to see if the final answer is stable to changes with different inputs from the aspect of judgements or priorities'. If the eigenvector of a criterion increases, the eigenvectors of the remaining criteria must decrease proportionately, and the global eigenvectors of the alternatives must be recalculated. Sensitivity analysis can also be used to determine the most important or critical criterion by computing the absolute or percentage amount by which the weight of any criterion must be changed in order to cause a switch in the ranking of either the top alternative or in any pair of alternatives[21].

Increasing or decreasing values of the eigenvector of the main criterion in a pairwise comparison matrix simulated for several scenarios. There was no change in the judgement evaluations in the final priority ranking when the eigenvector value of each criterion increased/decreased up to 6%. That is, the alternative 'A_4' can always be selected as the most convenient option for the plant location, and alternative 'A_3', 'A_2' and 'A_1' sequentially followed this alternative considering the final priorities.

The final decision found by the proposed FMADM model was compared with the simulated scenarios in Figure 5.

When the priority of the economy criterion is increased by 8%, alternative 'A_3' should be selected (Figure 5). It can be concluded from the sensitivity analysis that the final result of the proposed FMADM model is mainly sensible to the increase of economy criterion.

Application of the AHP method to solve the same problem

The AHP method is one of the most widely used MADM tools and can be successfully applied to various mining applications[22–26]. This is an eigen value approach to the pairwise comparison of components' attributes and alternatives. Some key and basic steps involved in this methodology are[12]:

1. State the problem
2. Broaden the objectives of the problem or consider all actors, objectives and its outcome
3. Identify the criteria that influence the behavior
4. Structure the problem in a hierarchy of different levels constituting goal, criteria, sub-criteria and alternatives
5. Compare each element in the corresponding level and calibrate them on the numerical scale. This requires $n \times (n-1) \div 2$ comparisons, where n is the number of elements with the considerations that diagonal elements are equal or 1 and the other elements will simply be the reciprocals of the earlier comparisons
6. Perform calculations to find the *CI, CR*, and normalized values for each criteria or alternative
7. If the λ_{max}, *CI* and *CR* are satisfactory then the decision is taken based on the normalized values; or else the procedure is repeated till these values lie in a desired range.

The AHP method was performed for the selection of the best plant location[15]. The hierarchy structure is given in Figure 3 and the eigen values in the Table II; IV–VII were used in the analysis. After constructing a pairwise comparisons matrix of main criteria as shown in Table II and sub-criteria of each main criterion as shown in Table IV-VII, the pairwise comparison of the alternatives based on the each sub-criterion should be performed. Thus, fifteen pairwise comparison matrices between the alternatives and each sub-group were obtained, and four matrices were constructed in order to calculate each alternative's final eigen values according to the main criteria. As there were four alternatives, the pairwise comparison matrix order was 4 × 4 for each sub-group. An example of pairwise comparison matrices for the land cost sub-criterion of the economy main criterion is presented in Table X.

After the construction of a pairwise comparison matrix of alternatives for the other sub-criteria of the economy main criterion (installation, transportation and tax reduction), another matrix was constructed to calculate the final eigen values of the economy main criterion. Table XI shows overall priorities calculated from the sub-criteria of the economy main criterion. It is readily observed from Table XI that the most suitable alternative is Denizli (A_4), which has the highest eigen value, when judged by the economy main criterion.

The final eigen values of the economy main criterion for each alternative is calculated by summing the product of the relative eigen values of each criterion and the relative eigen

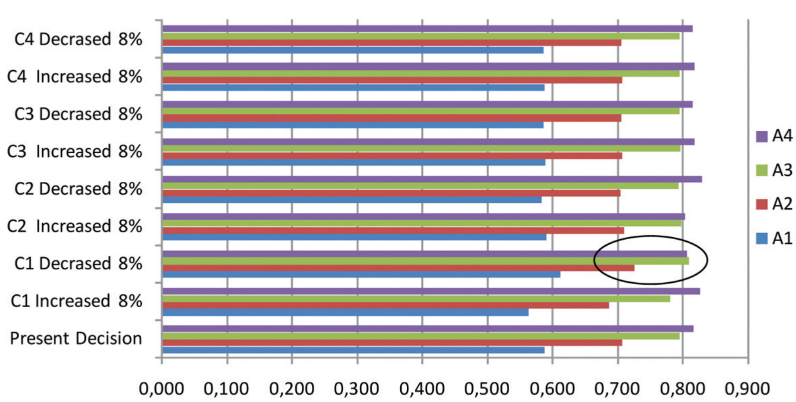

Figure 5—Sensitivity analysis results

Table X

Pairwise comparison matrix of alternatives based on land cost subcriteria

Land Cost (C_{11})	Eskisehir (A_1)	Bozuyuk (A_2)	Afyon (A_3)	Denizli (A_4)	Eigen Values
Eskisehir (A_1)	**1**	1/5	1/2	1/2	0.097
Bozuyuk (A_2)	5	**1**	3	3	0.533
Afyon (A_3)	2	1/3	**1**	1	0.186
Denizli (A_4)	2	1/3	1	**1**	0.186

λmax=4.004, CR=0.002≤0.1;OK

Table XI

Overall priorities of the economy main criterion

Economy (C_1)	C_{11}	C_{12}	C_{13}	C_{14}	Eigen values of economy criterion	Final eigen values of economy criterion
A_1	0.097	0.184	0.088	0.070	0.112	0.092
A_2	0.532	0.450	0.157	0.519	0.075	0.309
A_3	0.186	0.313	0.272	0.323	0.569	0.278
A_4	0.186	0.053	0.483	0.088	0.243	0.321

values of the alternative, considering the corresponding criteria. For example, the final eigen values of alternative A_1 is calculated as; (0.097 × 0.112) + (0.184 × 0.075) + (0.088 × 0.569) + (0.070 × 0.243) = 0.092.

In the same way, the other main criteria's final eigen values were calculated. So, the final matrix was constructed as shown in Table XII.

The overall rating of each alternative is calculated in the same way. Overall results in Table XII show that the Denizli alternative (A_4) should be selected as the optimum plant location because the priority of this alternative (0.310) is the highest value. In order to improve the quality of the results, a sensitivity analysis can be performed on the final outcome on the AHP analysis in the same way mentioned before.

In the FMADM analysis, Denizli (A_4) was found the most suitable alternative and the alternatives were ranked as: A_4, A_3, A_2 and A_1. Also, Denizli (A_4) was found to be the most suitable alternative in the AHP analysis and the alternatives were ranked as: A_4, A_2, A_3 and A_1. Of both of the analyses, A_4 was found to be the best and A_1 was found to be as the worst alternative. Only the order of the A_2 and A_3 alternatives were changed. However, after determining the eigen values of sub and main criteria in the AHP analysis, fifteen pairwise comparison matrices, four main criterion overall priority calculation matrices and one final matrix, a total of twenty matrices, were constructed. Generally, the pairwise comparisons are extremely bothering processes for the decision makers. However, the decision makers can reach the optimal solution after the determination of the each sub-criterion total eigen values constructing only one matrix in the FMADM applications.

Table XII

Overall results/final matrix

	Economy	Production	Marketing	Environmental	Overall results
A_1	0.092	0.106	0.286	0.223	0.123
A_2	0.309	0.329	0.278	0.131	0.299
A_3	0.278	0.226	0.149	0.508	0.268
A_4	0.321	0.340	0.288	0.138	0.310
Main criteria weights	0.581	0.257	0.094	0.068	

Conclusion

Travertine processing is one of the most important parts of the natural stone industry. Today, the investment cost of an average sized natural stone processing plant is about $5 million[1]. Because of the size of the investment, it is very important to determine the optimum natural stone plant location. The developed FMADM model from this study can be used for all natural stone types, and can generate an analysis for the worldwide natural stone industry.

DM applications can be applied for different branches of the mining industry. The number of criteria and alternatives should be considered by the decision maker in the DM, especially constructing pairwise comparison matrix applications because of the consistency and validity of the DM process[18–20]. The number of alternatives should be 7±2, otherwise the grouping method should be applied in the same way presented in this study.

The selection of the most convenient plant location involves the interaction of several subjective and objective factors or criteria. Decisions are often complicated and many even embody contradiction. In this study, both FMADM and AHP models were developed considering the four main criteria and fifteen sub-criteria. Among four alternatives under consideration, variant Denizli (A_4) is the most acceptable one with allowance for all main and sub-criteria in these analyses. However, a decision maker has to cope with several pairwise comparison matrices in the AHP method. This main disadvantage of the application of the AHP method can be overcome by employing the FMADM method in which fewer matrices are evaluated.

Unlike the traditional approach to plant location selection, FMADM is a more scientific method providing the integrity and objectivity of the estimation process. The model is transparent, and easy to comprehend and apply by the decision maker. The proposed method can be programmed to run effectively on relatively low-cost computing systems, thus providing the potential for wide-spread exploitation of the technique within the natural stone industry worldwide.

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