



Alternatives evaluation in EIA by spatial multi-criteria evaluation technique

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Abstract

Alternatives evaluation methodologies are applied to comparing plan or project alternatives and selecting optimal alternative in environmental impact assessment (EIA). In this research, spatial multi criteria evaluation (SMCE) technique was used for alternatives evaluation. The technique was used in geographical information system (GIS) and it enables GIS in decision making and alternatives evaluation spatially. Evaluation method in SMCE is according to multi criteria analysis. For the study, environmental assessment of a land use plan was considered. The non-action and land use plan alternatives were considered for evaluation. In non-action alternative, region development was not according to any designed plan. All of maps were made by raster model in GIS. The most important result in the research was possibility of environmental impacts and alternatives evaluation in GIS in spatial way. GIS could evaluate alternatives in EIA, the action that was impossible in the past. The used methodology advantages are such as quantitative present of impact magnitude, aggregation of data layers, quantitative and computerized methods for data layer standardization, ability in weighing impacts by quantitative and qualitative approaches, evaluating many numbers alternatives and considering different weigh methods for impacts and categories of environment.

Key words: EIA, GIS, SMCE, alternatives evaluation, environmental impacts.

Introduction

Different development aspects are accompanying with many impacts on environment. In this way, different methods and techniques were used to create balance and suitability between human activities and environment. Environmental impact assessment is useful method that it studies and assesses impacts of a project or plan on environmental factors. Environmental impact assessment of projects and development plans were done by approval of National Environmental Policy Act (NEPA).

Environmental assessment studies typically address a minimum of two alternatives, and they can include upwards of fifty alternatives. A two-alternatives study usually represents a choice between construction and operation of a project versus project non-approval. The alternatives to be addressed may encompass a wide range of considerations. There are different systematic methods which can be used for comparing and evaluating alternatives ¹. Following completion of all appropriate environmental impact assessment studies, the major task is to make the completed analyses productive to the decision-making process. The evaluation of alternatives must result in a clear, concise comparison that easily illustrates the tradeoffs involved between the build and no-build alternatives and the distinguishing degree of impact among the various build or action alternatives ².

A fully functional Geographical Information System (GIS) is an

integration of several components and subsystems. It is devoted especially to collect, store, retrieve and analyze spatially-referenced data ³. GIS was used in environmental assessments. The most important applications of GIS are overlaying maps, assessing cumulative impacts, making database, mapping ecosystems, mapping habitat potential, and making maps and data for environmental inventory study ⁴. Agrawal and Dikshit ⁵, Haltuch and Berkman ⁶, Vanderpoorten *et al.* ⁷ and Liu and others ⁸ mentioned general uses of GIS in EIA as follows:

* In project definition: During project identification and definition, the project proponent conducts feasibility studies and defines the usefulness of the study. GIS can be very well used for defining the project by showing the location of the project.

* In evaluating visual impacts: Using GIS the various types of visual impacts can be evaluated.

* In scoping system: GIS can serve as a basis for scoping of environmental effects. Once the basic databases are available, a GIS-based system may provide better-targeted guidelines for EIS.

* In impact significance determination: A spatial impact assessment methodology based on the assumption that the importance of environmental impact is dependent, among other things, on the spatial distribution of the effects and of the affected environment.

Recent surveys of GIS use in environmental assessment found

that while GIS is widely utilized, its use is largely limited to the basic GIS functions such as map production, classic overlay or buffering⁹. This utilization does not make full use of the spatial analysis and modeling capabilities of GIS^{9, 10}. GIS has several limitations in the domain of decision-aid. Therefore, it has limitation for application in alternatives evaluation and decision making in environmental assessment. The remedy suggested by some researchers is to integrate the GIS with different operations research/management science tools that have experienced very successful applications in different domains since the 1960s³. The most suitable family of analytical methods is that of multi criteria analysis (MCA).

Decision-making can be defined as the process of choices among alternatives. Multi-criteria decision analysis (MCDA), developed in the environment of operational research, aids analysts and decision-makers in situations in which there is a need for identification of priorities according to multiple criteria. This usually happens in situations where conflictive interests coexist.

The geographical information systems (GIS) support the solution of complex spatial problems, providing the decision-maker with a flexible environment in the process of the decision research and in the solution of the problem. The visualization of the context, structure of the problem and its alternative solutions is one of the most powerful components of a decision support system. Thus, the integration GIS–MCDA has the objective of favouring decision-makers, providing them with ways to evaluate several alternatives, based on multiple, conflictive criteria. Pereira and Duckstein¹¹ stress that the most important components of a multi-criteria technique are those that involve interaction with the decision-maker, to develop a value function or to elucidate a group of weights for the evaluation criteria. These steps usually require interactive questions. The current GIS packages do not possess these capacities of interactive questions, and the interaction between the analyst and the decision-maker takes place outside the GIS environment. An important advantage in using GIS to accomplish spatial multi-criteria analysis is the ease in developing criteria based on neighborhood analysis operations¹².

The role of GIS in spatial decision-making is to aid the decision-maker in designating priority weights to the criteria, to evaluate the feasible alternatives and to visualize the results of his choice^{13, 14}. The search usually results in the selection of a certain number of alternatives that satisfy minimum threshold values. The reduction of the set of alternatives and the selection of the best one usually require the use of multi-criteria techniques. Thus, improvement of the capacities of GIS in the decision-making can be achieved by the introduction of multi-criteria techniques in the GIS environment, some examples can be found in Srdjevic and *et al.*¹⁵, Hill *et al.*¹⁶, Liu *et al.*¹⁷, Joerin and Musy¹⁸, Keisler and Sundell¹⁹, Lin and *et al.*²⁰, Malczewski and Jackson²¹, Giupponi²², Sólnes²³ and Higgs²⁴. Malczewski²⁵ presents the state of the art in GIS–multi-criteria integration.

In the cases that the high degree of uncertainty and conflicting objectives are associated with decisions, multi-criteria evaluation tools make a valuable contribution to decision-making processes in environmental studies with GIS²⁶⁻³².

In this study, feasibility of environmental impacts and alternatives evaluation of a land use plan was studied by a GIS-MCA technique for the first time. The used technique was spatial multi-criteria

evaluation application (SMCE). The hypothesis was that SMCE could solve alternatives evaluation problem (in EIA) by GIS. In the study, maps will be used in MCA for decision making substitute of scores. The used GIS was ILWIS 3.2 academic (ILWIS-SMCE).

Materials and Methods

The study area was Robotkarim township as a case study in southwest of Tehran province, Iran (Fig. 1). Robotkarim township runs from 50°53' to 51°13' eastern longitude and from 35°20' to 35°35' northern latitude. It has 621,199 people, covering an area of 54,687 ha. For feasibility study of GIS application in alternatives evaluation by spatial multi-criteria evaluation technique, environmental assessment of a land use plan was considered. Therefore a land use plan was prepared in study area.

Preparation of land use plan: Land use planning was done by using Ecological Capability Evaluation Models of Iran integrated with socio-economical data in study area³³. All of land use planning steps were done in GIS. Ecological and socio-economical data layers were digitized and used in the GIS. At first step of land use planning, ecological capabilities of study area was determined. Thirty two digital maps (data layers) were used in ecological capability evaluation of study area. In the land use planning, land use components determination and qualitative classification were done for study area.

For ecological capability evaluation of study area, it is necessary the ecological factors of region were assessed by criteria (ecological models). Ecological models for land use identification were forestry and afforestation model (in eight classes), ecological conservation model (in ten classes), ecotourism model (in three classes), urban, rural, industrial and military model (two classes), aquiculture model and agriculture and range management model (in nine classes). According to ecological capability evaluation, the study area had ecological capability for afforestation, ecological conservation, second class of urban, industrial, rural and military development, third and fifth classes of agriculture and range land uses. The study area was unsuitable for forestry, ecotourism and aquiculture uses. At next step, socio-economical data were integrated with ecological evaluation results and then land use plan was prepared finally. According to the land use planning results, land use types were allocated to farming (15,547

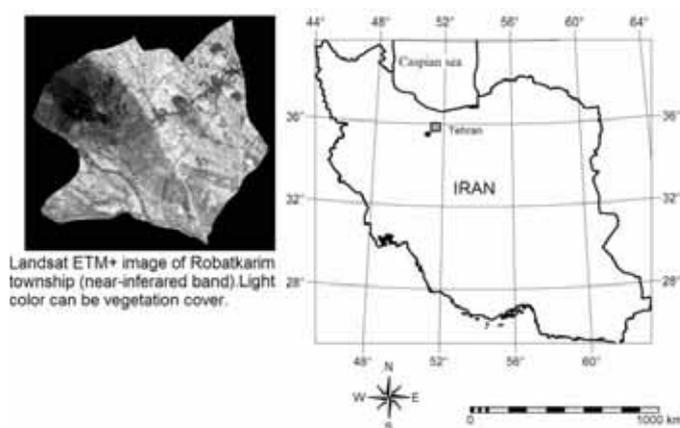


Figure 1. Geographical location of case study area (Robotkarim township), Iran.

ha), afforestation (793 ha), ecological conservation (29,449 ha) and urban, rural, industrial and military development (8,794 ha) in the study area.

Alternatives evaluation: ILWIS 3.2 was used as a GIS package and spatial multi-criteria evaluation (SMCE) was applied in the package. SMCE application assists and applies doing multi-criteria evaluation (MCE) in a spatial way. The input for the application is a number of maps of a certain area (so-called 'criteria'), and a criteria tree that contains the way criteria are grouped, standardized and weighed. The output of SMCE consists of one or more maps of the same area (the so-called 'composite index maps') that indicate the extent to which criteria are met or not in different areas and thereby support planning and/or decision-making.

At first, maps of environmental elements in three groups (ecological, socio-economical and cultural groups) were made by raster model in GIS. Twenty nine environmental elements were considered for evaluation and their maps were made. These maps were prepared by study of environmental inventory in the study area. The list of environmental elements can be concluded from Table 4.

Two alternatives were considered for alternatives evaluation: land use plan alternative (Alternative 2) and non-action alternative (Alternative 1). In non-action alternative, region development is not according to any designed plan. Every map of environmental elements was crossed with maps of two alternatives (plan maps). Maps of the land use plan and non-action alternatives consist of the land use types as activity factors.

One map integrated with a table was produced by cross action that has introduced spatially impacts of development plan in GIS. It is one of the SMCE advantages that presents magnitude and location of impacts. For determination of impacts scores, it is necessary that scales of impact importance is multiplied in impact magnitude. Therefore, two columns were demonstrated in table of map which resulted from crossing action (Fig. 2): one column in title of benefit that presents positive impact and another column (cost) that presents negative impacts. In GIS, there isn't positive or negative signs. Therefore, positive and negative impacts present in benefit and cost maps for every element of environment. Predefined scales of impacts importance had values between 0 and 5¹ that were inserted in benefit and cost columns manually (Table 1). Two maps as benefit impact and cost impact were made for every environmental element. There is a column in crossing table in title of area that introduced magnitude of impacts (Fig. 2) (Environmental impact score = Impact magnitude * Impact importance). Environmental impacts in the study were demonstrated in form of map in title of impact maps (equal to criteria) that titles of them are presented in Table 4. Every environmental element can produce two maps of benefit and cost

Table 1. Predefine scales for determination of environmental impacts importance.

Cost impact	Scale	Benefit impact
Very important	5	Very important
Important	4	Important
Moderately important	3	Moderately important
Unimportant	2	Unimportant
Most unimportant	1	Most unimportant
No impact	0	No impact

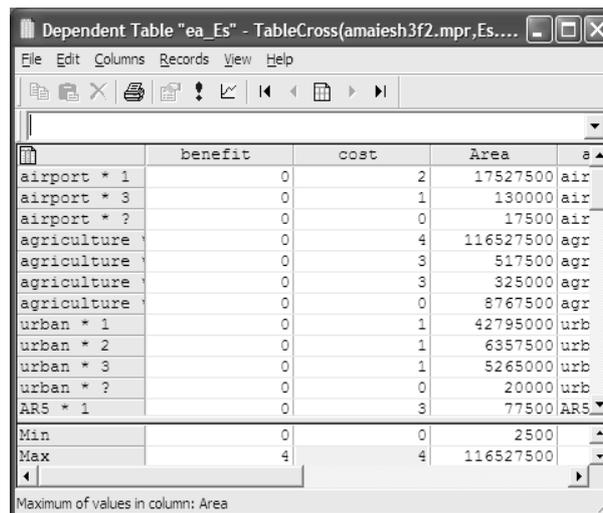


Figure 2. The crossing table. For example, the table of crossing land use plan map and classes map of erosion is presented.

that were presented positive and negative impacts of development on every factor of environment respectively which are called impact maps. Fifty eight benefit and cost impact maps were demonstrated according to 29 environmental elements. The predefined scales of impacts importance were belonged to pixels of maps.

Insert impact maps to SMCE: The place of processing data layers in ILWIS-SMCE is in criteria tree. Criteria tree is a window that impact maps and development plan alternatives were inserted to system (Fig. 3). The criteria tree collects all information regarding hierarchical relation of objectives, criteria and indicators, the priorities (weights) of these and the standardization settings. Three groups were selected according to affected environments: ecological, socio-economical and cultural groups. Then, benefit and cost maps of 29 environmental

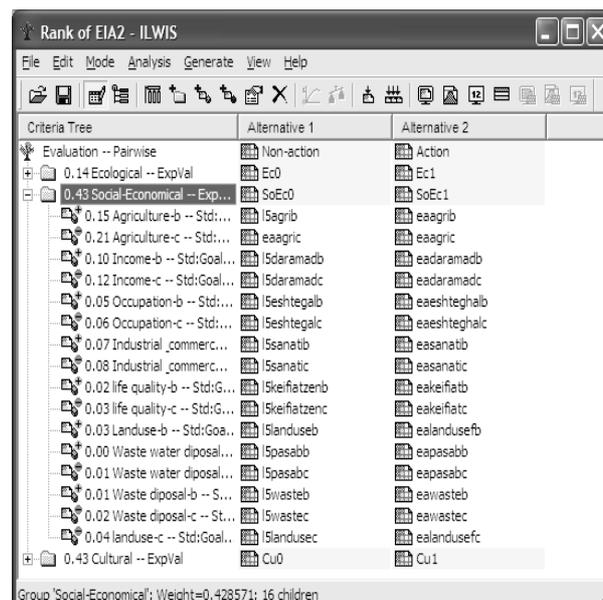


Figure 3. Criteria tree in SMCE-ILWIS software interface showing hierarchy of objectives and criteria, weights and standardization functions.

factors were inserted in criteria tree in every group.

Standardizing impact maps: In order to compare criteria together in a way that makes sense, they had to be standardized, i.e., transformed to the same unit. In standardization, the map or column values were converted to values between 0 and 1. In this study, environmental impact maps had value domain. For standardization, the goal method was used. The input values with a linear function that uses a specified minimum and maximum value were standardized in ILWIS-SMCE in spatially format. The following formulas for standardization were used: Benefit factor = (value - minimum input value)/(maximum goal value - minimum input value) (Formula 1); Cost factor = 1 - (value - minimum input value)/(maximum goal value - minimum input value) (Formula 2). The output of the standardization is positive values for pixels of both the cost and benefit impact maps. The standardized values are exactly between 0 and 1.

Relative weighting: In alternative evaluation, there are multiple impact maps and affected environmental groups, and then the evaluation may needs to be weighted in order to indicate the relative importance of the maps and environmental groups. In this study, pairwise comparison method was used for weighting of groups. Weights are numbers between 0 and 1. The sum of the weights of the groups equals 1.

Pairwise comparison: The qualitative pairwise comparison method assumes that the user compares the relative difference of importance between all unique pairs of criteria³⁴. The user specifies the relative importance for each pair of factors in fixed qualitative phrases (e.g., Criterion 1 is much more important than Criterion 2 and little more important than Criterion 3) or with a slide bar. From these phrases, normalized weights are calculated. This scale is presented in Table 2 for a binary relation.

Also environmental impacts were weighted by direct and ranking methods. For better conclusion and comparison, two relative weigh methods were used in the study. In direct method, equal weights were considered for all of impacts and weights were considered manually. Ranking method is from importance weighting methods to decision factors (environmental impacts). Ranking techniques involve the rank order of decision factors in their relative order of importance. If there are n decisions factor, rank ordering would involve assigning the value of 1 to the most important factor, 2 to the second-most important, and so forth, until n is assigned to the least important factor. It should be noted that the rank order numbers could be revised; that is, n could be assigned to the most important factor, $n-1$ to the second-most- important factor, and so forth, until 1 assigned to the least important factor¹. The main problem of the technique is that the different between factor weights are not precise, for example 1 is assigned to the least important factor and 4 to the fourth important factor but the difference of these factors is not 4 times.

Table 2. Scales of binary relation in pairwise comparison³³.

Binary relation	Scale	Binary relation	Scale
Equally preferred	1	More strong preference	6
Very weak preference	2	Demonstrable preference	7
Weak preference	3	More demonstrable preference	8
Rather strong preference	4	Absolute preference	9
Strong preference	5		

In order to solve the problem, ranking weights were normalized in this study. Janssen and Van Herwijnen³⁵ illustrated a new approach for normalization of problems. The title of this method is expected value method. The expected value method assumes each set of weights that fits the rank order of criteria has equal probability. The weight vector is calculated as the expected value of the feasible set. This method results in a unique weight vector.

$$W_k = \sum_{i=1}^{n+1-k} \frac{1}{n(n+1-i)}$$

In combination with, for example, weighted summation it also results in a complete ranking of the alternatives.

The method calculates the weight, w_k , for criterion k according to Formula 3 where n is the number of criteria. The weights fit the rank order of criteria defined by set S , meaning that $w_1 \geq w_2 \geq \dots \geq w_n \geq 0$.

Environmental impact maps were weighted by the method in ILWIS-SMCE. They were sorted from the most important to the least and weighted.

Results and Discussion

Every value in impact maps (decision factors) were standardized between 0 and 1 according to Formula 1 and 2. The result of weighting environmental groups by pairwise comparison method is presented in Table 3. The weights were normalized between 0 and 1. The socio-economical and cultural groups have equal weights and more than ecological group. In the weighing, human

Table 3. Normalized weights of environmental groups according to pairwise comparison.

Group	Land use plan	Non-action (Regional development without any plan)
Ecological	0.14	0.14
Socio-economical	0.43	0.43
Cultural factors	0.43	0.43

needs were the most important goal.

The weights of environmental impact maps by Direct method were equal for all of impact maps and factors. The relative weights of environmental impacts by ranking method are presented in Table 4. The weights were inserted to impacts of ecological, socio-economical and cultural groups. These weights are for determination of relative importance of impacts. For every environmental element, there are two benefit and cost impact maps that are presented by b and c letters respectively because of every factor of the land use plan or non-action alternatives can have negative or positive effects on environmental elements. Impact maps are presented in title of every environmental element that was impacted by the plan development. The most values of weights were inserted to vegetation cover production and sensitive habitat items in ecological group. Agriculture, income, cultural buildings and health items have gotten the most weights in socio-economical and cultural groups.

After standardization and weighting, impact maps (value maps) were aggregated in every alternative quantitatively. In result, every alternative that was obtained more score after aggregation, therefore, it had more positive impacts. The scores of alternatives

Table 4. Resulted relative weights of impacts maps by ranking method in different environmental groups. Impact maps are presented in title of every environmental element that was impacted by the plan development.

Ecological		Socio-economical		Cultural	
Erosion-b:	0.032	Agriculture-b:	0.149	Cultural buildings-b:	0.110
Erosion-c:	0.035	Agriculture-c:	0.211	Cultural buildings-c:	0.143
Soil fertility-b:	0.018	Income-b:	0.097	Landscape-b:	0.010
Soil fertility-c:	0.021	Income-c:	0.118	Landscape-c:	0.021
Surface water quality-b:	0.005	Occupation-b:	0.049	Recreation-b:	0.034
Surface water quality-c:	0.006	Occupation-c:	0.058	Recreation-c:	0.048
Surface water quantity-b:	0.003	Industrial - commerce-b:	0.069	Teaching-b:	0.065
Surface water quantity-c:	0.004	Industrial - commerce-c:	0.081	Teaching-c:	0.085
Ground water quality-b:	0.027	life quality-b:	0.023	Health-b:	0.243
Ground water quality-c:	0.030	life quality-c:	0.028	Health-c:	0.243
Ground water quantity-b:	0.023	Land use -b:	0.034		
Ground water quantity-c:	0.025	Land use-c:	0.041		
Plant production-b:	0.096	Waste water disposal-b:	0.004		
Plant production-c:	0.127	Waste water disposal-c:	0.008		
Vegetation density-b:	0.042	Waste disposal-b:	0.013		
Vegetation density-c:	0.050	Waste disposal-c:	0.017		
Sensitive plantation-b:	0.070				
Sensitive plantation-c:	0.080				
Habitat-b:	0.013				
Habitat-c:	0.014				
Aquatic ecosystem-b:	0.001				
Aquatic ecosystem-c:	0.002				
Range carrying capacity-b:	0.055				
Range carrying capacity-c:	0.062				
Wildlife-b:	0.009				
Wildlife-c:	0.011				
Air quality b:	0.042				
Air quality c:	0.042				
Noise b:	0.018				
Noise c:	0.018				
Wildlife diversity b:	0.009				
Wildlife diversity c:	0.009				

were obtained by the resulted formula in the research (Formula 4).

$$\text{Alternative score} = \sum_{i=1}^m [(\sum_{i=1}^n (VM \times RWI)) \times RWG]$$

VM = score of every impact map [$\Sigma(\text{Pixel value} \times \text{NP})$], RWI = relative weight for every map, RWG = relative weight of every environmental group, n = number of maps in every environmental group, m = number of environmental groups, Pixel value = The specified pixels value after standardized in every map, NP = number of pixels related to the specified pixels. The above relation was also used for every environmental group.

The predefined scales were used because of the land use plan and non action alternatives have different factors and impacts on a specified environment. The relative weights present different rank and importance between elements of environment. Using two steps in weigh is important subject.

In weighting impacts maps by Direct weigh method, land use plan alternative and non-approval alternative have got 123,368.99 and 115,036.99 scores respectively after aggregation. Then, land use plan has been selected for development plan in Robotkarim township according to evaluation of development plan impacts on ecological, socio-economical and cultural factors groups. The used methodology can perform the impacts aggregation in every

group and alternatives separately. The land use plan has obtained less scores in the cultural groups. Therefore, non-action is more optimal than the land use plan in this group.

In weighting impact by ranking method, land use plan alternative has got more score than non-approval alternative (Table 5), therefore it was selected alternative. The scores of ecological and cultural groups in non-approval alternative are more than land use plan alternative. In contrast, the score of socio-economical group in land use plan alternative is more than non-approval alternative. According to Table 5, scores of environmental groups are changed by using Direct and ranking weigh methods. For example, scores of ecological groups were

Table 5. Scores aggregation of environmental impacts in three groups and scores of alternatives.

Weigh method for impacts	Group	Alternative 2: Land use plan development	Alternative 1: Non-action
Direct weigh	Ecological	120,050.08	119,309.54
	Social-economical	134,699.65	111,576.79
	Cultural	112,869.94	117,718.16
	Sum	123,368.99	115,036.99
Ranking weigh	Ecological	130,520.82	132,914.47
	Social-economical	138,242.25	125,523.03
	Cultural	113,424.32	114,603.11
	Sum	125,999.53	121,531.24

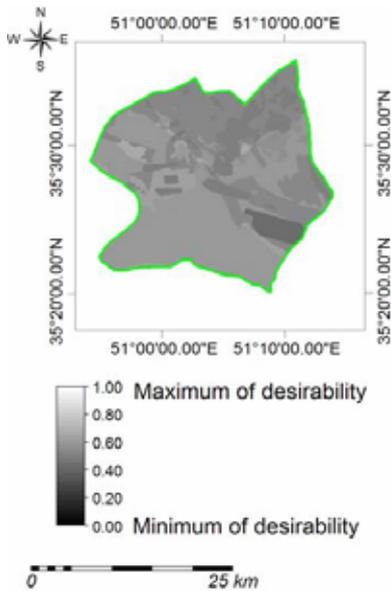


Figure 4. Composite index map of the land use plan of Robatkarim Township.

changed in action and non-action alternatives by different used weighing methods. It is concluded the relative importance of environmental impacts has important rule in decision-making in EIA.

It is possible that GIS presents desirability of development plan visually. For this presentation, composite index map was prepared (Fig. 4). The map was made from aggregation cost and benefit maps of development impacts on environment factors. In other words, the output map was the result of the weighted-sum formulas and the standardization formulas. Values of composite index map are between 0 and 1. Numbers 1 and 0 present the most desirability and minimum desirability respectively.

For evaluation of spatial multi-criteria evaluation method for appropriateness of EIA, Objective Criteria method was used for selecting an environmental evaluation method according to Warner and Preston guides³⁶. The key areas of evaluation process of objective criteria method are as cost/time effectiveness criteria, impact identification, impact measurement, impact assessment and communication that every key area has some criteria.

Specifications of SMCE technique were compared with criteria in Key areas. Correlation of SMCE specifications and Objective Criteria method were determined by 1, 2 and 3 scales. 1, 2 and 3 denote criteria completely satisfied, criteria partially satisfied and criteria not satisfied respectively. Spatial multi-criteria evaluation in GIS has obtained 1 scale in spatial dimension, aggregation, credibility, quantitative, commensurate, alternative comparison and communicability criteria.

Spatial multi-criteria evaluation was designed according to GIS problems in decision-making. The used methodology can evaluate data that has geographical specifications additional of descriptive specification. It is enabled GIS for alternatives evaluation and optimal selection by multi-criteria evaluation methods. Therefore, GIS could evaluate alternatives in EIA, the action that was impossible in the past. In this study, environmental impact and alternatives evaluation were possible by GIS. The methodology and study results have some important capabilities for EIA such

as: a) Weighing methods which are used for impacts and different environmental groups such as AHP and ranking methods; b) Standardizing methods that are very important in dimensionless of impacts scales; c) Aggregation of environmental impacts; d) Determination of magnitude and location of environmental impacts by GIS capabilities.

These capabilities enable GIS for alternatives evaluations in EIA. There is not any limitation in number of data layers for overlying and alternative evaluation. Many numbers of alternatives can be evaluated by SMCE technique. The method is more efficient for environmental impact assessment of plans and programs than industrial projects because of spatial efficiency of GIS. The resulted methodology is a very useful conclusion for Strategic Environmental Assessment (SEA) according to environmental impact assessment of plans and program.

There are some studies about using multi-criteria evaluation in GIS which were mentioned in introduction section, but there was not any study about application of these two tools in alternatives evaluation in EIA. The results of the study have presented the required process for alternatives evaluation by GIS. The resulted methodology has been presented with required process for alternatives evaluation in a spatial way (GIS) in Fig. 5.

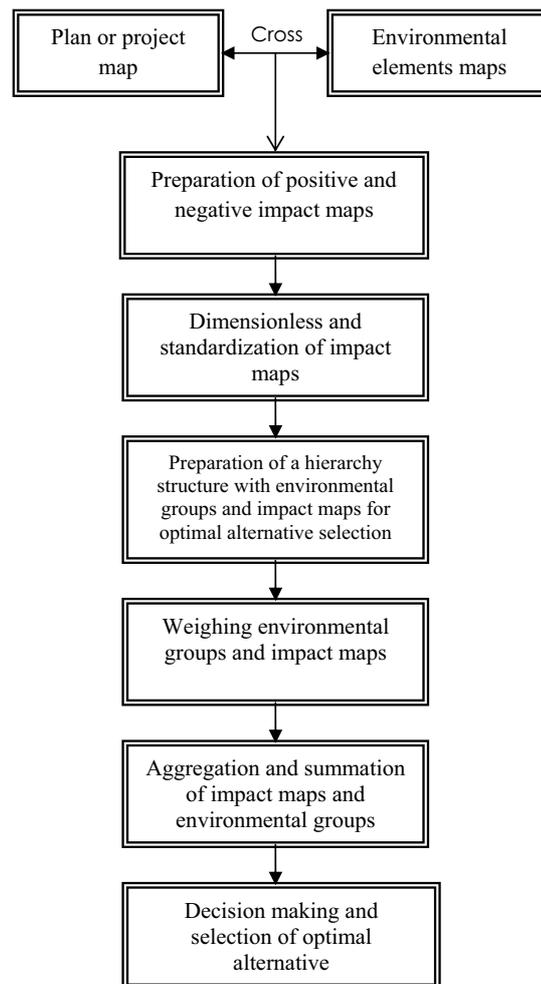


Figure 5. Presentation of the concluded methodology for alternative evaluation in EIA by a spatial way (GIS).

References

- ¹Canter, L. W. 1996. Environmental Impact Assessment. McGraw-Hill, Inc., 657 p.
- ²Marriott, B.B. 1997. Environmental Impact Assessment: A Practical Guide. McGraw Hill, New York, 320 p.
- ³Chakhar, S. 2003. Enhancing geographical information systems capabilities with multi-criteria evaluation functions. *Journal of Geographic Information and Decision Analysis* **7**(2):47–71.
- ⁴Treweek, J. 1999. Ecological Impact Assessment. Blackwell Science, 351 p.
- ⁵Agrawal, M.L. and Dikshit, A.K. 2002. Significance of spatial data and GIS for environmental impact assessment of highway projects. *Indian Cartographer* **22**:262–265.
- ⁶Haltuch, M.A. and Berkman, P.A. 2000. Geographic information system (GIS) analysis of ecosystem invasion: Exotic mussels in Lake Erie. *Limnology and Oceanography* **5**:1778–1787.
- ⁷Vanderpoorten, A., Sotiaux, A. and Engelsm, P. 2005. A GIS-based survey for the conservation of bryophytes at the landscape scale. *Biological Conservation* **121**:189–194.
- ⁸Liu, Y. B., De Smedt, F., Hoffmann, L. and Pfister, L. 2005. Assessing land use impacts on flood processes in complex terrain by using GIS and modeling approach. *Environmental Modeling and Assessment*, pp. 227–235.
- ⁹Joao, E. M. 1998. Use of geographic information systems in impact assessment. In Porter, A.L. and Fittipaldi, J.J. (eds). *Environmental Methods Review: Retooling Impact Assessment for the New Century*. The Press Club, North Dakota, pp.110–121.
- ¹⁰Schaller, J. 1990. Geographical information system applications in environmental impact assessment. In Scholten, H. J. and Stillwell, J. C. H. (eds). *Geographical Information Systems for Urban and Regional Planning*. Kluwer Academic Publishers, Dordrecht, pp. 107–117.
- ¹¹Pereira, J. and Duckstein, L. 1993. A multiple criteria decision-making approach to GIS-based land suitability evaluation. *International Journal of Geographical Information Systems* **7**:407–424.
- ¹²Gomes, E.G. and Lins, M.P.E. 2002. Integrating geographical information systems and multi-criteria methods: A case study. *Annals of Operations Research* **116**(27):243–269.
- ¹³Jankowski, P. 1995. Integrating geographical information systems and multiple criteria decision-making methods. *International Journal of Geographical Information Systems* **9**(3):251–273.
- ¹⁴Antunes, P., Santos, R. and Jordão, L. 2001. The application of geographical information systems to determine environmental impact significance. *Environmental Impact Assessment Review* **21**(6):511–535.
- ¹⁵Srdjevic, B., Medeiros, Y. D. P. and Faria, A. S. 2004. An objective multi-criteria evaluation of water management scenarios. *Water Resources Management* **18**(1):35–54.
- ¹⁶Hill, M. J., Lesslie, R., Donohue, R., Houlder, P., Holloway, J., Smith, J. and Ritman, K. 2006. Multi-criteria assessment of tensions in resource use at continental scale: A proof of concept with Australian rangelands. *Environmental Management* **37**(5):712–731.
- ¹⁷Liu, C., Frazier, P., Kumar, L. and Macgregor, C. 2006. Catchment-wide wetland assessment and prioritization using the multi-criteria decision-making method TOPSIS. *Environmental Management* **38**(2):316–326.
- ¹⁸Joerin, F. and Musy, A. 2000. Land management with GIS and multicriteria analysis. *International Transactions in Operational Research* **7**:67–78.
- ¹⁹Keisler, J. and Sundell, R.C. 1997. Combining multi-attribute utility and geographic information for boundary decisions: An application to park planning. *Journal of Geographic Information and Decision Analysis* **1**(2):101–118.
- ²⁰Lin, H., Wan, Q., Li, X., Chen, J. and Kong, Y. 1997. GIS-based multicriteria evaluation for investment environment. *Environment and Planning B* **24**:403–414.
- ²¹Malczewski, J. and Jackson, M. 2000. Multicriteria spatial allocation of educational resources: An overview. *Socio-Economic Planning Sciences* **34**:219–235.
- ²²Giupponi, C., Eiselt, B. and Ghetti P. F. 1999. A multicriteria approach for mapping risks of agricultural pollution for water resources: The Venice Lagoon watershed case study. *Journal of Environmental Management* **56**(4):259–269.
- ²³Sólnes, J. 2003. Environmental quality indexing of large industrial development alternatives using AHP. *Environmental Impact Assessment Review* **23**(3):283–303.
- ²⁴Higgs, G. 2006. Integrating multi-criteria techniques with geographical information systems in waste facility location to enhance public participation. *Waste Management & Research* **24**(2):105–117.
- ²⁵Malczewski, J. 1996. A GIS-based approach to multiple criteria decision making. *International Journal of Geographical Information Systems* **10**:955–971.
- ²⁶Bascetin, A. 2007. A decision support system using analytical hierarchy process (AHP) for the optimal environmental reclamation of an open-pit mine. *Environmental Geology* **52**(4):663–672.
- ²⁷Tarrasón, D., Ortiz, O. and Alcañiz, J. M. 2007. A multi-criteria evaluation of organic amendments used to transform an unproductive shrubland into a Mediterranean *dehesa*. *Journal of Environmental Management* **82**(4):446–456.
- ²⁸Gómez-Delgado, M. and Tarantola, S. 2006. Sensitivity analysis, GIS and multi-criteria evaluation for a sustainable planning of a hazardous waste disposal site in Spain. *International Journal of Geographical Information Science* **20**(4):449–466.
- ²⁹Khadam, I. M. and Kaluarachchi, J. J. 2003. Multi-criteria decision analysis with probabilistic risk assessment for the management of contaminated ground water. *Environmental Impact Assessment Review* **23**(6):683–721.
- ³⁰Jiang, H. and Eastman, J. R. 2000. Application of fuzzy measures in multi-criteria evaluation in GIS. *International Journal of Geographical Information Science* **14**(2):173–184.
- ³¹Carey, P. D., Short, C., Morris, C., Hunt, J., Priscott, A., Davis, M., Finch, C., Curry, N., Little, W., Winter, M., Parkin, A. and Firbank, L. G. 2003. The multi-disciplinary evaluation of a national agri-environment scheme. *Journal of Environmental Management* **69**(1):71–91.
- ³²Dey, P.K. 2002. An integrated assessment model for cross-country pipelines. *Environmental Impact Assessment Review* **22**(6):703–721.
- ³³Makhdum, M. *et al.* 2001. *Environmental Evaluation and Planning by Geographical Information System*. Tehran University Press, 304 p.
- ³⁴Saaty, T. 1980. *The Analytical Hierarchy Process*. McGraw Hill, New York, NY.
- ³⁵Janssen, R. and Van Herwijnen, M. 1994. *Multiobjective decision support for environmental management + definite decisions on a finite set of alternatives: Demonstration disks and instruction*. Kluwer Academic Publishers, Dordrecht (Netherlands), 232 p.
- ³⁶Asian Development Bank 1997. *Environmental Impact Assessment for Developing Countries in Asia*. Asian Development Bank Publications, 349 p.