Multi-Objective Decision Making for Land Use Planning with Ordered Weighted Averaging Method

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Abstract

Multi-objective decision making is common in environmental engineering management. A compromise solution to the multi-objective problems under conditions of conflicting objectives with GIS-based Ordered Weighted Averaging (OWA) method is investigated. In some instances, decisions may be based on a single criterion, but commonly several criteria are required to define the decision set. Ordered Weighted Averaging (OWA) is a relatively new Multi-Criteria Evaluation (MCE) method. In GIS-based OWA method, both criteria weights and order weights are considered. Calculation method of order weights based on Orness, and construction method of comparison matrix for criteria weights based on analytical hierarchy program (AHP), are introduced; Multi-objective decision making of this method is investigated. As an example, GIS-based OWA method is applied to Tangshan City, and some advice is proposed for engineering design.

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Keywords: Multi-Objective; MCE; OWA; decision-making; conflicting objectives; engineering disaster prevention;

1. Introduction

GIS has become a necessary system in many fields, such as resource investigation, environment observation and disaster prevention, city planning and management decision-making, project planning and construction, and especially in decision-making analysis [1,2]. GIS-based MCE method is the foundation of decision-making. There are two fundamental classes of multi-criteria evaluation in GIS: one is the Boolean overlay operation based on Boolean calculation of intersection (AND) and union (OR), and the other is weighted combination based on evaluation criteria with sequential standardization, which includes conventional weighted linear combination (WLC) method and ordered weighted averaging (OWA) method that is a relatively new method[3]. In weighted combination methods, a factor with a high criterion weight can tradeoff or compensate for poor weights on other factors. WLC method is situated at the mid-point on the continuum ranging from the MIN (Boolean ‘AND’ operator) to MAX (Boolean ‘OR’ operator), which indicates full tradeoff among criteria; OWA method can select any degree of tradeoff among criteria between no tradeoff and full tradeoff according to the decision-making strategy. Therefore, Boolean overlay represents the extreme cases with no tradeoff, Boolean ‘AND’ operator represents the MIN risk
decision making, and Boolean ‘OR’ operator represents the MAX risk decision-making in strategy. WLC method is an averaging risk decision-making with full tradeoff among criteria; OWA method can obtain any results from the MIN risk to MAX risk with appropriate tradeoff.

OWA operators was introduced by Yager in 1988 [4], and quantifier guided aggregation was given in 1996 [5]. Salem Chakhar et al. (2003) discussed the combination between GIS and multi-criteria evaluation, and the enhancing capabilities for GIS with multi-criteria evaluation functions [6]. Jacek. Malczewski (2004, 2006) analyzed GIS-based multi-criteria evaluation for land-use suitability and the application of OWA method to identify the most suitable lands for housing development[7, 3]. About OWA method, many results have been obtained for calculation of OWA operators, and applied to many domains without GIS environment, such as business evaluation, multi-attributes decision-making, and image analysis, and so on[8-12].

Multi-objective decision making is common in environmental management, but it is not yet further developed within GIS. With conflicting objectives, land can be allocated to one objective but not more than one. One possible solution lies with a prioritization of objectives. After the objectives have been ordered according to priority, the needs of higher priority objectives are satisfied before those of lower priority ones. This is done by successively satisfying the needs of higher priority objectives and then removing areas taken by that objective from consideration by all remaining objectives. However, instances are rare where a prioritized solution makes sense, so more often a compromise solution is required. Compromise solutions to the multi-objective problem have most commonly been approached through the use of mathematical programming tools outside GIS. In the case of raster GIS, because of the massive data sets, a solution to the problem of multi-objective problems under conditions of conflicting objectives is investigated. The procedure is an extension of single objective problems. Each of the suitability maps may be thought of as an axis in a multi-dimensional space. As example application, this method is applied to GIS-based multi-criteria evaluation for land use in Tangshan City.

2. GIS-Based OWA Method

For one cell (spatial location or pixel) i, \( z_{ij} \) is the sequence of attribute values by reordering from maximum value to minimum value, \( v_j \) is the j-th order weight, and \( u_j \) is the j-th criterion weight, OWA is defined as follows [1],

\[
OWA_i = \sum_{j=1}^{n} \left( \frac{u_j v_j}{\sum_{j=1}^{n} u_j v_j} \right) z_{ij}
\]  

In which, the key is to calculate order weights and criterion weights. The criterion weights are assigned to evaluation criteria to indicate their relative importance. All locations on the j-th factor are assigned the same weight of \( u_j \). The order weights are associated with criterion values, and order weights are determined by their rank ordering across factors at each location (pixel). The j-th factor on different location with different rank order is assigned with different order weight.

A measure of Orness and Trade-off, associated with a particular set of weights can be obtained by the following equations [2].

\[
Orness = \sum_{j=1}^{n} \frac{n-j}{n-1} v_j
\]

In which, \( Orness \in [0,1] \)

\[
Tradeoff = 1 - \sqrt{\frac{n \sum_{j=1}^{n} (v_j - \frac{1}{n})^2}{n-1}}
\]

There are many methods to calculate order weights \( v_j \) in formula (1), an effective method is to calculate order weights \( v_j \) according to Orness (change from 0 to 1, see table 1). Xu Zeshui provides three methods for the calculation of order weights with given orness degree [9]. One of them is fuzzy quantifier. For \( Orness = c \), randomly generates \( n+1 \) nonnegative real number \( p_0, p_1, p_2, \ldots, p_n > 0 \), (i=1,2,…, n), and \( p_0=0 \). Then, calculate \( q_i \) and \( c^j \), as follows,
\[ q_i = \sum_{j=1}^{i} p_{ij} s_j = q_n c = \sum_{i=1}^{n-1} s_i/(n-1)(i = 0,1,\ldots, n) \quad (4) \]

If \( c' > c \), go to formula (5) and (6), order weights \( v_j \) can be calculated. Otherwise, go to formula (7) and (8) to calculate order weights.

\[ c = c/c', \quad s'_n = s_n, \quad s'_i = s(i = 0,2\ldots n-1) \quad (5) \]

\[ v_i = s'_i - s'_{i-1} \quad (6) \]

\[ s'_{i+1} + it, \quad \sum_{i=1}^{n-1} s'_i / s_n/(n-1) = c \quad (7) \]

\[ v_i = (s'_i-s'_{i-1}) / s'_n \quad (8) \]

There are many methods to calculate criterion weights in formula (1), and analytical hierarchy program (AHP) represents the relative important degree of factors subtly. Construction of comparison matrix is the most important in AHP, generally, 9-point continuous rating scale is adopted, which is shown as table 1. Thus, the comparison matrix produced by this technique, is a positive reciprocal matrix. Therefore, only the higher/lower triangular half which includes \( n(n-1)/2 \) elements needs to be filled in.

Maximum latent root \( \lambda_{\text{max}} \) in comparison matrix \( A \), eigenvector is \( W \), the calculation of criterion weights is to calculate eigenvector \( W \), makes,

\[ AW = \lambda_{\text{max}} W \quad (9) \]

The calculation of eigenvector as follows

\[ a_{ij} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \quad i, j = 1,2,\ldots, n \quad (10) \]

Then plus by row,

\[ \overline{W}_i = \sum_{j=1}^{n} a_{ij} \quad i, j = 1,2,\ldots, n \quad (11) \]

Vector \( \overline{W} = [\overline{W}_1, \overline{W}_2, \ldots, \overline{W}_n]^T \) is standardized as follows,

\[ W_i = \frac{\overline{W}_i}{\sum_{j=1}^{n} \overline{W}_j} \quad i, j = 1,2,\ldots, n \quad (12) \]

Eigenvector \( W = [W_1, W_2, \ldots, W_n]^T \) is obtained. But consistency verification is necessary, and Maximum latent root \( \lambda_{\text{max}} \) is calculated firstly, as follows,
\[
\lambda_{\text{max}} = \sum_{i=1}^{n} \left( AW \right)_i / nW_i
\]  

(13)

In which, \( (AW)_i \) represents the i-th element in \( AW \), consistency index (C.I.) is calculated as follows,

\[
\text{C.I.} = \frac{\lambda_{\text{max}} - n}{n - 1}
\]  

(14)

Consistency ratio (C.R.) is calculated with randomly consistency index (R.I.), as follows,

\[
\text{C.R.} = \frac{\text{C.I.}}{\text{R.I.}}
\]  

(15)

Value of consistency ratio less than 0.10 indicates good consistency. When value exceeds 0.10, the comparison matrix needs to be modified, and the matrix of weightings should be re-evaluated.

3. Multi-Objective Decision Making

The procedure for multi-objective problems is illustrated by the diagram in Figure 1. Each of the suitability maps may be thought of as an axis in a multi-dimensional space. Every raster cell in the image can be located within this decision space according to its suitability level on each of the objectives. To find the best area for Objective 1, we simply need to move a decision line down from the top (i.e., far right) of the Objective 1 suitability axis until enough of the best raster cells are captured to meet our area target. We can do the same with the Objective 2 suitability axis to capture the best area for it. This partitions the decision space into four regions—areas best for Objective 1 and not suitable for Objective 2, areas best for Objective 2 and not suitable for Objective 1, areas not suitable for either, and areas judged best for both. The latter represents areas of conflict.

![Fig. 1. Procedure for multi-objective problems](image)

The ideal point represents the best possible case—a cell that is maximally suited for one objective and minimally suited for anything else. Since the conflict region will be divided between the objectives, both objectives will be short on achieving their area goals. As a result, the process will be repeated for both objectives to gain more territory. The process of resolving conflicts is iteratively repeated until the exact area targets are achieved. However, unequal weighting can be given, which has the effect of changing the ratio of the weights assigned to those objectives.
4. An Example Application

This method is applied to site safety evaluation in Tangshan City, and there are four influencing factors. The first disaster factor is goaf collapse, the second disaster factor is karst collapse, the third disaster factor is earthquake, and the fourth factor is site type. Ascend sigmoid function is selected for goaf collapse, with point a equals to 0, point b equals to 750. Descend J-shaped function is selected for karst collapse, with point c equals to 0, point d equals to 12035. Ascend sigmoid function is selected for earthquake, with point a equals to 0, point b equals to 19000. Ascend J-shaped function is selected for karst collapse, with point c equals to 1000, point d equals to 6000.

According to the evaluation criteria in figure 1, the results of single criterion are obtained, such as the suitability of site condition is shown as figure 2. According to analytical hierarchy program (AHP) method, the relative importance between factors can be expressed by a significant value, and this value can be used in comparison matrix. After comparison among disaster factors, comparison matrix is constructed. According to formula (9) to (13), criterion weights for goaf collapse, karst collapse, earthquake, and site types are calculated. The results are 0.2077, 0.1164, 0.6248, and 0.0511. According to formula (14) and (15), consistency ratio is 0.04, it is less than 0.10, which indicates good consistency.

After the calculation of criterion weights, order weights are also calculated. According to the formula (5) to formula (9) with Orness=0.75, order weights are, 0.5781, 0.1875, 0.1406, 0.0938, and the suitability image is shown as figure 3. Figure4 is the results of WLC. Through the comparison of figure 4 and figure 5, it is found that maximum suitability increases from 173 (WLC results) to 210 (OWA results), and this makes the favorable area increase. Because low risk strategy is rational, more favorable areas for construction are obtained with appropriate safety suitability.

Once the multi-criteria suitability maps have been created for each objective, the multi-objective decision problem can be approached. The conflicts map is shown as figure 4 and the final result map is shown as figure 5.

Therefore, the multi-objective problem is solved through standardizing the single-objective suitability maps and allocating the best ranked cells to each objective according to the areal goals.

5. Conclusions

The single objective multi-criteria evaluations are solved through establishing the criteria, standardizing the criteria, establishing factor weights and undertaking the multi-criteria evaluation. And, the multi-objective problem is solved through standardizing the single-objective suitability maps and allocating the best ranked cells to each objective. OWA method is applied to the suitability evaluation of construction engineering landuse for industry and residence in Tangshan City successfully. The validity and practicability of OWA method are proved.
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Acknowledgements

This work is supported by National Natural Science Foundation of China (50678059) and Natural Science Foundation of Hebei Province (D2010000922, E2009000757, 09277130D).

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