Multicriteria Decision Analysis Techniques, Challenges, and Potentials For Water Resources Management Scenario Analysis

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Abstract

Due to an increase in water demand triggered by global conditions such as climate change, population growth, rapid urbanization, and so on, water resources management becomes an important issue for the sustainability of water resources. Decision-making is the final step in the management process. Very often, when a decision becomes a bit or completely complicated because it has to consider a complex or multi-criteria approach. That's why we need tools that can help decision-makers deliver sophisticated decisions. This paper will briefly discuss three methods of Multi-criteria Decision Analysis Techniques: the ELECTREE Method, the PROMETHEE Method, and the Analytical Hierarchy Process (AHP). The AHP method shows that the priority is placed on different levels. The first level lies in the overall benefit from the realization of the project, as the main goal of the hierarchy. The ELECTREE and PROMETHEE Methods are widely used for outranking problems. Both methods are often used for analysis in different fields such as agriculture and water management. Considering the huge impact of projects in the water resources management sector, the Multi-criteria Decision Analysis Technique will become more challenging in the future.

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Introduction

Nowadays, the demand for water is increasing due to several factors such as population growth, expansion of business activity, and rapid urbanization. Conversely, the amount of fresh water is decreasing due to climate change, depletion of aquifers, and water pollution. Therefore, the management of water resources has become an important issue. Water resources are sources of water that are useful or potentially useful for humans. Concerning human activity, the uses of water include agricultural, industrial, household, recreational, and environmental sectors that require fresh water [5].

According to the definition from the World Bank [6], water resources management is the integrating concept for many water sub-sectors. The use of an integrated water resources perspective ensures that social, economic, environmental, and technical dimensions are considered in the management and development of surface water (rivers, lakes, and wetlands) and groundwater. Problems will arise when considering the integration of management between different water sectors because they have their objectives for each sector. In complex problems, for example, in a situation where multiple criteria are involved, we need a method that satisfies solving the problem. Multi-criteria decision analysis (MCDA) is a well-known method as a decision-making tool developed for complex problems.

Every step of our lives has resulted from decisions. Sometimes a decision is easy, but very often it becomes complicated because it's surrounded by a complex or multi-criteria approach. To deliver sophisticated decisions, Multi-Criteria Analysis (MCA) can be considered a tool for problem-solving. It's a framework for evaluating decision options against multiple criteria. Multi-criteria analysis (MCA) is a decision-making tool developed for complex multi-criteria problems that include qualitative and/or quantitative aspects of the problem in the decision-making process.

This paper will briefly discuss some analytical techniques that have been widely used to solve the problem of the multi-criteria approach in water resources management. Those techniques are the ELECTRE Method, the PROMETHEE Method, and the Analytical Hierarchy Process Method (AHP). Together with the rising climate change problems on our earth, water resources management will become more challenging in the future. We agree that sometimes the efficiency or effectiveness of water resources management is as much a political as a scientific challenge, which not only requires an expert in each multi-discipline but also the integration of key stakeholders into multi-objective, multi-criteria decision-making processes. This situation requires knowledge to gain an understanding of the problem for a diverse user group and to address not only hydrological and environmental engineering but also economic and social components directly.

I- The Project Ranking Decision Problem

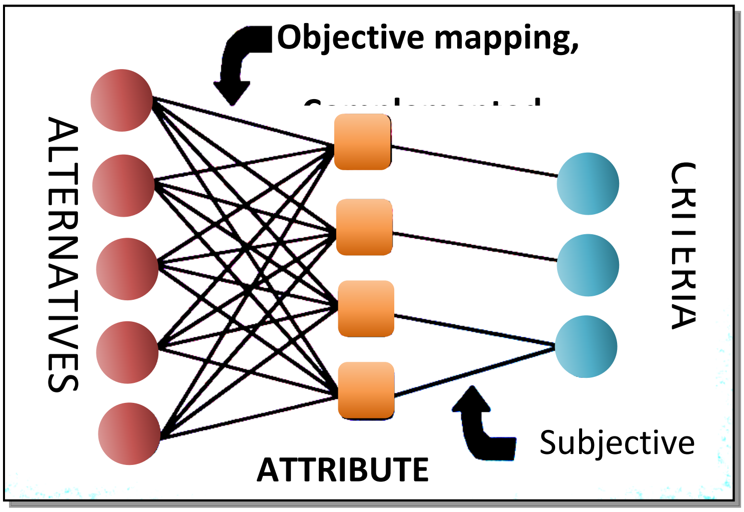

Figure 1. Mapping of Alternative-Attribute-Criteria [1]

To construct project rankings, decision-makers involved in the planning process are often faced with complex problems. The decision-maker has to take into account necessary categories such as economic, socio-political, technical, and environmental factors for their project ranking decision. According to the paper [1], the project ranking problem is, like many decision problems, challenging for at least two reasons. First, there is no single criterion that adequately captures the effect or impact of each project; in other words, it is a multiple-criteria problem. Second, there is no single decision-maker; instead, the project requires consensus from a group of decision-makers.

A good decision suggests that, where possible, the subjective and objective parts of the decision process should be separated (Henig and Buchanan, 1996 in [1]). The purpose of separation between subjective and objective aspects is to guide decision-makers away from unnecessary subjectivity and toward a more objective orientation. Buchanan and Sheppard (1999) defined a decision problem as comprising two components: a set of objectively defined alternatives and a set of subjectively defined criteria. The relationship between the alternatives and the criteria is described using attributes, which are the objectives and measurable features of alternatives. The mapping of the relationship of alternatives, attributes, and criteria is shown in Figure 1.

II. ELECTRE Method

The acronym ELECTRE stands for "Elimination Et Choix Traduisant la REalite" (Elimination and Choice Expressing Reality). A typical ELECTRE approach is based on substitution rates. These rates were ill-defined (stakeholders' views about their values strongly differed), and it is only possible to fix a minimum and maximum value for each one. On such a basis, a set of embedded fuzzy relations has been defined; it is known as ELECTRE I. The method of ELECTRE II was born in the late sixties; this method deals with the problem of ranking actions from the best option to the worst. Just a few years later, a new method of ELECTRE was defined (ELECTRE III). The main ideas introduced by this method were the use of pseudo-criteria and fuzzy binary outranking relations. Another ELECTRE method known as ELECTRE IV has arisen, which was triggered by the problem of the Paris subway network. Using this method becomes possible to rank actions without using the relative criteria importance coefficients, and it was equipped with an embedded outranking relations framework [2].

Situations which are suitable for using the ELECTREE method are [2]:

1. There are at least three criteria available to be considered by the decision-maker (DM). And, at least one of the following situations must be verified:2.

3. Actions are evaluated on an ordinal scale or interval scale. However, these scales are not suitable for comparing differences.

4. Among criteria, there should exist a strong heterogeneity related to the nature of evaluations.

5. Compensation for the loss on a given criterion by a gain on another one may not be acceptable for the DM. Therefore, such situations require the use of a non-compensatory aggregation procedure.

Indifference and preference thresholds are required to evaluate a significant value.

ELECTRE has developed from I to IV, but those methods are constructed on the same fundamental concepts, and they have their characteristics when applied to real problems. Based on each characteristic of the method, we shall concentrate on ELECTRE III, which is suitable for application to project ranking.

According to Buchanan and Sheppard (1999), there are two important concepts related to the ELECTRE approach: thresholds and outranking. Assume that there exist defined criteria, gj, j = 1,2,...,r, and a set of alternatives, A. The procedure of ELECTRE III is discussed as follows [1]:

1. The preference modeling is constructed using three relations for two alternatives $(a,b) \in A$:

aPb (a is preferred to b) | $g(a) > g(b)$

aIb (a is indifferent to b) | $g(a) = g(b)$

aJb (a cannot be compared to b).

2. An indifference threshold q is introduced by the decision-maker; therefore, the relationship of that preference would be as follows:

aPb (a is preferred to b) | $g(a) > g(b) + q$

aIb (a is indifferent to b) | $|g(a) - g(b)| \leq q$

aJb (a cannot be compared to b) remains.

3. An intermediate area is recognized between preference and indifference, where the decision-maker hesitates between preference and indifference. This area is defined as a weak reference (Q relation). After introducing an additional preference threshold, p, and relation Q, the model becomes:

aPb (a is strongly preferred to b) | $g(a) - g(b) > p$

aQb (a is weakly preferred to b) | $q < g(a) - g(b) \leq p$

aIb (a is indifferent to b; and b to a) | $|g(a) - g(b)| \leq q$

4. Build the outranking relationship for each of the r criteria. To say aSjb means that "a is at least as good as b concerning the jth criterion".

5. Develop outranking relationships with two kinds of schemes they are concordance and discordance.

- The jth criterion is in concordance with assertion aSb if and only if aSjb. That is, if $gj(a) \geq gj(b) - qj$. Thus even if gj(a) is less than gj(b) by an amount up to qj, it does not contravene the assertion aSjb and therefore is in concordance

- The jth criterion is in discordance with assertion aSb if and only if bPja. That is if $gj(b) \geq gj(a) + pj$. That is, if b is strictly preferred to a for criterion j, then it is not in concordance with the assertion that aSb.

6. Define the measurement of the strength of the assertion aSb. This measure is called the concordance index C(a,b) for a given pair of alternatives $(a,b) \in A$. If kj is a weight for criterion j, then we define the value of the outranking relation as follows:

$C(a,b) = \frac{1^r\,1^r}{KjKj}$ kjcj(a,b), where k = $\sum_{j=1}^{r} Kj \sum_{j=1}^{r} Kj$

Where :

$$C(a,b) = \begin{cases} 1, \text{ if } gj(a) + qj \geq gj(b) \\ 0, \text{ if } gj(a) + pj \leq gj(b) \\ \Theta, \text{ if in between} \end{cases}$$

And,

$$\theta = \frac{Pj+gj(a)-gj(b)Pj+gj(a)-gj(b)}{Pj-qj \qquad Pj-qj}$$

From the ELECTRE III procedure, we can define which preference alternatives are represented by an outranking, and finally, it should be considered by decision-makers to make a decision. In general, the advantage of ELECTREE is that this method can solve different problems using diverse inter-criteria and intra-criteria analyses, and also analyze various quantities of outranking relationships (Roy & Bouyssou, 1993, in [12]). However, ELECTREE IV has a specific advantage which does not make use of weights; this method works using concepts such as outranking and pseudocriteria, where the decision agent does not need to determine weights for criteria. In this way, the solution is obtained using a sequence of grouped outranking relationships (Roy & Hugonnard, 1982, in [12]).

III. PROMETHEE Methods

Another method widely used in solving project ranking for multicriteria problems is PROMETHEE. The history of PROMETHEE began in 1982; PROMETHEE I is used for partial ranking, and PROMETHEE II is dedicated to complete ranking, both of which were developed by J.P. Brans. A few years later, J.P. Brans and B. Mareschal developed two more methods: PROMETHEE III and IV. PROMETHEE III focuses on ranking based on intervals, while PROMETHEE IV handles continuous cases. Two more PROMETHEE methods, PROMETHEE V (MCDA including segmentation constraints) and PROMETHEE VI (representation of the human brain), were also developed by J.P. Brans and B. Mareschal in 1992 and 1994 [8].

In PROMETHEE, additional information is needed to consider multicriteria problems. For instance, if one alternative is better on criterion s and the other is better on criterion r, it is impossible to decide which is the best one without additional information. The additional information requested by PROMETHEE consists of information between the criteria and information within the criteria. In multicriteria problems, some obvious definitions indicate the dominant relation between criteria, where the definitions, respectively denoted as P, I, and R, stand for preference, indifference, and incomparability. To translate those relations regarding the criteria, we should refer to mathematical relations as follows [8]:

For each $(a,b) \in A$:

$$aPb \begin{cases} \forall j : gj(a) \geq gj(b) \\ \exists k : gk(a) > gk(b) \end{cases}$$

$\forall j : gj(a) = gj(b)$ aIb

$$\exists s : gs(a) > gs(b)$$

aRb

$$\exists r : gr(a) < gr(b)$$

Considering project ranking, a later discussion will focus on PROMETHEE I & II. Similar to the ELECTREE method, here in PROMETHEE, the first step is the construction of a preference model. To construct the model, two kinds of information are needed:

• Information between the criteria • Information within each criterion

Information between the criteria involves the weighting of each criterion. The weight represents the relative importance of different criteria, and the values of the weights are non-negative numbers. The more important a criterion is, the higher its weighting number reflects. To assign a weight value in PROMETHEE, there is software available (PROMCALC and DECISION LAB) that helps the user introduce arbitrary weight numbers.

The basic idea in the preference structure of PROMETHEE is pairwise comparison. Based on this idea, a comparison of deviation between two alternatives on a particular criterion is considered. A small deviation means a small preference, and the larger the deviation, the larger the preference. Preference ranges between 0 and 1, and the representative formula for preference is illustrated as follows [8]:

$$Pj(a,b) = Fj\ [dj(a,b)]\ \forall a, b \in A,$$

Where :

$$Dj(a,b) = gj(a) - gj(b)$$

And for which

$$0 \leq Pj(a,b) \leq 1$$

The preference equals 0 when the deviations are negative. The alternative function for minimized criteria is defined as [8]:

$$Pj(a,b) = Fj\ [-dj(a,b)]$$

IV.1 Preference and Outranking Flows

In 1985, Brans and Vincke suggested different shapes for Fj. Regarding the preference function $Fj(a,b) \in [0,1]$, which reflects the preference of a over b for criterion gj, Fj(a,b) increases if gj(a) – gj(b) is large and equals zero if $gj(a) \leq gj(b)$. A specific preference function for every criterion is needed as a prerequisite in outranking flows. The weight value is another requirement for outranking procedures. The value is non-negative and ranges between 0 and 1.

Based on the preference and weight value for every pair of alternatives (a,b), the outranking degree $\pi(a,b)$ would be:

$\pi(a,b) = \sum wjFj(a,b)/\sum wj$

Based on the obtained outranking degrees, a leaving flow $\Phi+$ and an entering flow $\Phi-$ are computed for each alternative as follows :

$$\Phi+ (a) = \sum b \neq a\ \pi(a,b),$$

$$\Phi- (a) = \sum b \neq a\ \pi(b,a).$$

IV.2 PROMETHEE I and II

Partial ranking solutions by PROMETHEE I are obtained from the positive ($\Phi+$) and negative ($\Phi-$) outranking flows. They are independent flows that do not induce each other. The information from both outranking flows is consistent and may therefore be assured. For example, if correlation aPb indicates that a higher power of a is associated with a lower weakness of a concerning b. However, there are often situations in which a comparison between criteria appears inconsistent. This occurs when a is good on a set of criteria on which b is weak, and conversely, b is good on some other criteria on which a is weak. In this case, we have to be more careful and consider both alternatives as incomparable [8]. With partial ranking, certain alternatives may remain incomparable [9]. The decision-maker should take responsibility for deciding the best action because no fixed decision comes from PROMETHEE I. The last two points are considered disadvantages of PROMETHEE I.

PROMETHEE II consists of complete ranking. The net outranking flow can then be considered as [8]:

$$\Phi(a) = \Phi+(a) - \Phi-(a)$$

The advantage of complete ranking as provided by PROMETHEE II, in comparison to partial ranking by PROMETHEE I, is that there are no remaining alternatives incomparable; all the alternatives are comparable. However, calculating the difference of outranking flows in PROMETHEE II might cause more information to be lost, resulting in more disputable information, which is considered a disadvantage of PROMETHEE II. Considering that both methods have their own strengths and weaknesses, it is recommended to analyze the problem using both methods in real situations.

IV.3 THE ANALYTICAL HIERARCHY PROCESS (AHP)

To measure decisions involving both tangible and intangible criteria, the AHP method supposes that the measurement is based on judgment and the knowledge of expert people, as well as existing measurements and statistics.

AHP is a systematic procedure for dealing with complex decision-making problems in which many competing alternatives (projects, actions, scenarios) exist. This method was developed and published in the 1970s [4]. Some advantages of the hierarchy concept are [4]:

- The hierarchy evaluation is based on pairwise comparisons. The most effective way to concentrate judgment is to take a pair of elements and compare them on a single property without concern for other properties or other elements.

- A hierarchy does not need to be complete, meaning an element in a given level does not have to function as an attribute for all the elements below it.

- A hierarchy is not a traditional decision tree. Each level may represent a different cut at the problem.

In the process of making a decision, as the first step, the decision-maker compares two alternatives, Ai and Aj, using a criterion and assigns a numerical value to their relative weight. The representative value from the result of comparison is between 1 and 9; there are no negative values. One expresses that Ai. Aj contributes equally to the objectives, and 9 expresses that the evidence favoring Ai over Aj is of the highest possible order of affirmation. Given that the n elements of a level are evaluated in pairs using an element of the immediately higher level, an n x n comparison matrix is obtained.

The comparison matrix shows consistency if and only if aij x ajk = aik for all i, j, k. The inconsistency of judgment measurement by AHP is determined by calculating the consistency index (CI) of the matrix.

$$CI = \frac{\lambda \max - n}{n-1}$$; λmax is the principal eigenvalue of the matrix

The next step is to define the consistency ratio (CR). CR value is obtained by the value of consistency index CI divided by the average random consistency index RI.

$$CR = CI / RI$$

The RI index is a constant value for an n x n matrix, resulting from a computer simulation of n x n matrices with random values on the 1-9 scale, where aij = 1/aji. The matrix is considered consistent if the value of CR is less than 5% for a 3x3 matrix, 9% for a 4x4 matrix, and 10% for larger matrices. Once the values are defined, the matrix comparisons become clear. Furthermore, the local priority of each matrix element concerning the higher-level criterion is calculated. Higher-level calculations involve using the current level element to calculate the higher intermediate level, and so on, until the lowest level of the hierarchy is reached. The lowest-level elements signify their relative contribution to achieving the overall goal.

DISCUSSION

Some methods presented above provide an overview of decision analysis techniques that can be used to solve the water resources management problem in multi-criteria approaches. In the case of water resources planning [3], a hierarchy is formed, which includes the parameters involved in the problem. In a hierarchy, the method shows that the priority has been placed at different levels. The level illustrates the contribution of each priority to the overall goal. At the first level lies the overall benefit from the realization of the project, serving as the main goal of the hierarchy. Another paper [11] shows that AHP determines the priorities of each alternative by analyzing the judgmental matrices and by applying the mathematical theory of eigenvalues and eigenvectors. Subjective and objective perspectives in AHP are combined in the form of a ratio from a simple pairwise comparison.

PROMETHEE and ELECTREE are best known for the outranking method. In these methods, the interaction of the decision method with the weighting of criteria becomes an important process. However, in problems where it is not possible to obtain the weights, it is possible to use ELECTRE III with equal weights [9]. Both methods are characterized by an aggregation of criteria, where the multicriteria value is replaced by a single criterion and a complete dominance relation is established [11]. Enrichment of the dominance relation is achieved by adding arcs to the dominance relation and/or by building "fuzzy" dominance relations. The use of outranking relation is a decision aid itself; however, it should be noted that outranking methods, in a way, narrow the choices (Shafike et al., 1992 in [11]). Both methods are often used in different fields of agricultural and water management. PROMETHEE is used for the analysis and assessment of the financial viability of agribusinesses (Baourakis et al., 2002), for simultaneous kinetic-spectrophotometric determination of carbamate pesticides (Ni et al., 2004), and for ranking different agricultural production options (Parsons, 2002). ELECTRE is used for the evaluation of floodplain restoration alternatives (Zsuffa and Bogardi, 1995), combined with GIS in the model MEDUSAT for assessing land suitability in Switzerland (Joerin et al., 1998), and also for outranking a series of water pricing policies in the Ebro river basin of the Huesca region in Spain (Breuil et al., 2000) [4].

Regarding the integrated approach with PROMETHEE and AHP or ELECTREE and AHP, they have their objection, which is good if their objection is combined to solve problems in multi-criteria approaches. For example, in a real case, the AHP method is responsible for determining weights for every criterion. With these criteria, we can construct a hierarchy that expresses a priority comparison between criteria. After a hierarchy is constructed, then PROMETHEE or ELECTREE takes responsibility for obtaining the final ranking, and we can experiment by changing the weights to see the sensitivity of the analysis.

CONCLUSION

Tools for decision aid in water resources management are increasingly necessary for the future. Facing global climate change on our Earth means we should carefully manage our natural resources, especially water resources. PROMETHEE, ELECTREE, and AHP are tools suitable for analyzing multi-criteria approaches in water resources management. Some realities about water resource projects, such as [10]:

- Wide-ranging impacts of water resource projects on society, the environment, and economic development

- Long-term impacts of water resource projects

- Difficulty in monetarily quantifying social and environmental impacts, often leading to lack of transparency

These factors become the technical analyses for making sophisticated decisions in multi-criteria approaches to water resources management, which remains an important issue for the future.

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