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# A HIERARCHICAL MULTIPLE CRITERIA MODEL FOR ELICITING RELATIVE PREFERENCES IN CONFLICT SITUATIONS*

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**Abstract**

A multiple criteria decision analysis (MCDA) approach is designed for capturing the relative preference information of a decision maker involved in a conflict. More specifically, an MCDA approach based on the outranking method, ELECTRE III, is employed for ranking states or possible scenarios in the conflict from most to least preferred, where ties are allowed, for a decision maker according to his or her value system. To demonstrate how this preference elicitation methodology can be conveniently implemented in practice within the framework of the Graph Model for Conflict Resolution, it is applied to a real world water supply crisis which occurred in the town of North Battleford, located in the Canadian province of Saskatchewan.

**Keywords:** Multiple criteria decision analysis, graph model for conflict resolution, ELECTRE III, fuzzy, preferences

## 1. Introduction

A strategic conflict is a decision situation in which two or more decision makers (DMs) are in dispute over some issue. Due to the fast growing global population and limited resources, water related conflicts bring challenges to the entire world (Salman 2006, Wolf 2002, Wolf et al. 2005). This serious situation requires some practical methodologies to examine and resolve it. The Graph Model for Conflict Resolution (GMCR) (Fang et al. 1993) is such a methodology that can be used to capture key characteristics of strategic conflict and provide decision support not only for the conflict participants, but also for anyone else who is interested in the outcomes of strategic conflicts.

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For example, a mediator, third party or regulator may wish to employ GMCR for gaining a better understanding of the conflict under study in order to guide it towards a more favorable result or a win/win situation. GMCR constitutes a general systems thinking approach to formally studying conflict. Hence, it is not restricted to applications to any particular field of study and has been applied to a broad range of areas, including environmental management, labor-management negotiation, military and peace-keeping activities, international economic negotiation, arms control, international logistic conflict activities, and so on (Kilgour & Hipel 2005). Hipel et al. (2008) explain how GMCR, along with other systems tools, can be employed within an adaptive integrative management framework in the field of water resources and elsewhere.

When investigating a real world conflict situation, GMCR follows the two main phases consisting of modeling and analysis. At the modeling stage, the participants involved in the conflict, also called the decision makers (DMs) or players, must first be identified. Each DM has one or more options to satisfy his or her objectives. A state, also referred to as an outcome or a scenario, is formed by a combination of options that DMs may or may not choose. The third important input parameter at the modeling stage is each DM's relative preferences over all of the feasible states in the model. In a graph model representation, a DM can change his or her option selection to cause a conflict to move from one state to another in a process called state transition, in order to maximize his or her benefit according to his or her preferences.

Analyses are performed once an appropriate model is in place. In particular, after calibrating the conflict model, one can make use of the structure of the model to extensively study possible strategic interactions among DMs as they jockey to improve their positions. Stability analysis is a procedure to study the potential moves and countermoves by DMs during the evolution of a conflict and to determine the most likely resolutions under a range of solution concepts describing potential human behavior under conflict. More specifically, a state is stable for a DM if he or she has no motivation to move away from it. A state that is stable for all of the DMs is called an equilibrium. The output of the stability analysis can be used to enhance decision making by providing a better understanding of the conflict and suggesting how a given DM may wish to behave in order to reach the best possible strategic result given the sociological constraints of the dispute.

GMCR II (Hipel et al. 1997, Fang et al. 2003a, 2003b) is a user-friendly decision support system (DSS) that implements the GMCR (Fang et al. 1993) methodology. In addition to the analysis and simulation tool for conflict participants, GMCR II can also be used by mediators, a third party or regulators as an instrument for investigation and communication purposes.

Among the three major input parameters into GMCR II, the DMs, each DM's options or courses of action, and each DM's relative preferences over the feasible states, preference information is the most important and sensitive input required for calibrating a model and subsequently carrying out a stability analysis. Each DM's relative preferences reflect his or her objectives or goals, under a given conflict situation. In GMCR II, a flexible methodology is available for ranking all of the feasible states from most to least preferred, where ties are allowed. In particular, option weighting, option prioritizing, and direct ranking constitute the three techniques for conveniently obtaining relative preferences. When employing option weighting, a user assigns option weights to reflect the relative importance of options from a given DM's viewpoint. In option prioritization, hierarchical preference statements are given in terms of one or more options and logical combinations thereof. Direct ranking permits a user to fine-tune the ranking of states that have first been ordered according to option weighting or option prioritization. For some small disputes, the user may wish to directly order the states without any prior ordering.

In practice, preference information is often difficult to obtain, even when using the aforementioned preference elicitation techniques. Other GMCR research regarding preferences includes: the strength of preference (Hamouda et al. 2004, 2006, Xu et al. 2009), unknown preferences (Li et al. 2004), emotions (Obeidi et al. 2005, 2009), attitudes (Inohara et al. 2007, Bernath Walker et al. 2009) and fuzzy concepts in preference analysis (Al-Mutairi et al. 2008, Hipel et al. 2011). However, a flexible preference method is needed that directly takes into account the values or criteria underlying a given DM's relative preferences in combination with preference uncertainty. Accordingly, the objective of this research is to develop a more comprehensive approach to preference elicitation which reflects the values or criteria of a given DM for ranking states, thereby expanding and enriching preference elicitation technique for utilization with GMCR II. In particular, obtaining a ranking of states according to preference for a given DM is structured as a multiple criteria decision analysis (MCDA) problem in this research.

As an evaluation method, MCDA can be used to generate the ranking of the decision alternatives on the basis of multiple criteria (Hobbs & Meier 2000, Belton & Stewart 2002, Figueira et al. 2005, Hajkowicz 2007). Vinke (1992) divided MCDA methods into three categories: 1) multiple attribute utility theory (Keeney & Raiffa 1976, Keeney 1992), 2) outranking methods (Roy 1968, 1978, 1989, 1996, Brans 1982, Brans & Vincke 1985, Brans et al. 1986), and 3) interactive methods (Benayoun et al. 1971, Dyer 1973, Saaty 1980, Xu & Chen 2007, Xu 2009). Among these categories, an outranking method is suitable for obtaining a DM's relative preferences in GMCR. Specifically, the ELECTRE family of methods is one of the most widely used ranking approaches because of its sound and flexible design, as explained below. In this paper, a three-layer hierarchical analysis approach, which employs a fuzzy multicriteria model of ELECTRE III (Roy 1978), is presented to elicit relative preference information for ordering states. The fuzzy characteristic enables the decision makers, or other relevant parties, to study the individual behaviors more realistically and comprehensively (Al-Mutairi 2008, Hipel et al. 2011).

In this preference elicitation approach, a criterion layer is introduced as the first layer. Then, an action layer is embedded between the criterion and option layers and serves as a bridge connecting these two layers in a conflict model. This extra layer clarifies the relationships between criteria and options. By using criteria instead of only options, this hierarchical analysis model can assist users in reflecting more precisely on a DM's preferences or values and fully attaining his or her standards of reasonableness in ranking states. Therefore, the result is more consistent and predictable. Moreover, the use of the ELECTRE III algorithm allows the model to deal with quantitative as well as qualitative information. Based on fuzzy relations, this algorithm can also handle preferences with uncertainties. Hence, it improves the acquisition of relative preferences for each DM when employing GMCR. More notably, this method provides a systematic procedure for determining preference in a form that can be input into the DSS of GMCR II.

In addition to GMCR, this preference elicitation approach can be employed with other related conflict analysis methodologies, including metagame analysis (Howard 1971), conflict analysis (Fraser & Hipel 1984), and drama theory (Howard 1999, Bryant 2003). Finally, in the foregoing conflict analysis methods, states or alternatives are defined in terms of options available to the DMs. When it is not clear which criterion should be used in the preference elicitation technique employed in this paper, one could use an approach such as the value focused thinking method of Keeney (2002) to assist in structuring this aspect of the methodology.

The remainder of this paper is organized as follows. The three-layer hierarchical analysis model and relative preference calculation procedure are presented in detail in the next section. By applying this approach to the tainted water supply debacle which took place in North Battleford, Saskatchewan, Canada, the practicality and effectiveness of this method are illustrated. Conclusions and insights are provided in the final section.

## 2. A Three-Layer Hierarchical Analysis Model for Relative Preferences

As mentioned previously, the hierarchical structure introduced in this section constitutes an additional complementary approach for the graph model, which is used to generate the relative preferences for each DM. This preference information is required before a stability analysis of the calibrated model can be carried out to find the potential equilibria and obtain other strategic insights. Figure 1 presents the framework of this model. The criteria in this MCDA model reflect the value system or objective of a specified DM while the states in the model are analogous to alternatives in a usual MCDA study. Also note that different DMs have different preferences, so that this procedure needs to be repeated for each DM.

Before going into the details describing the procedure of this hierarchical analysis model, some concepts and definitions for this model are defined as follows:

- A *criterion* is a standard, upon which a decision or judgment is based (Merriam-Webster's Collegiate Dictionary 1998). More precisely, "a criterion is a real-valued function on the set A of alternatives, such that it appears meaningful to compare two alternatives *a* and *b* according to a particular point of view on the sole basis of the two numbers $g_i(a)$ and $g_i(b)$" (Bouyssou 1990), where $g_i(a)$ is a real number (quantity assessment) that reflects the performance of $a$ on the $i$th criterion.

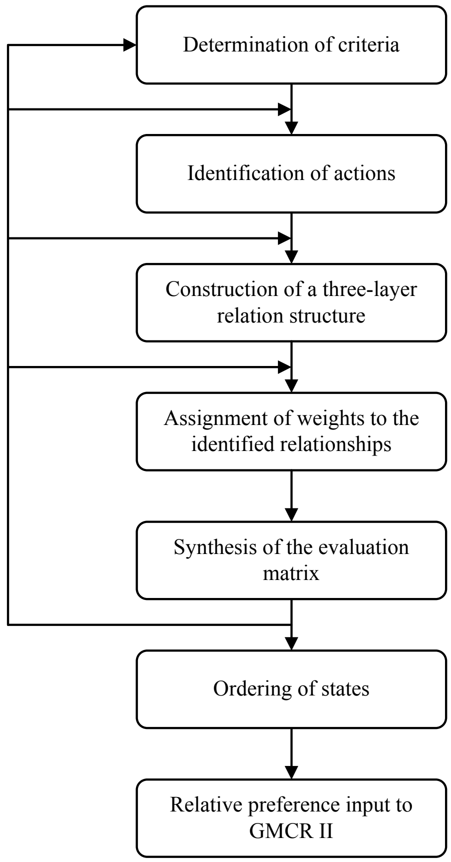


**Figure 1** The framework of a three-layer hierarchical analysis model for relative preferences

- An *action* is a deed that can be carried out to satisfy one or more criteria. Roy's (1996) general concept of action is employed here to give further explanation: "an action is the representation of a possible contribution to the comprehensive decision that can be considered autonomously with respect to the decision process development state and that can serve as an application point for the decision aid."
- An *option* is a feasible combination of actions.
- A *state* is a combination of options, also called an alternative, for which a ranking of all states reflects the relative preferences of a given DM in GMCR.

## 2.1 Determination of Criteria

First of all, the objectives of a given DM should be obtained. In conflict situations, different DMs usually consider different, often contradictory, criteria to evaluate the alternatives. A set of criteria is determined according to the DM's primary interest. Let $C=\{c_1,c_2,...,c_m\}$ denote the set of criteria, where $m$ is the number of criteria.

The overall objective for a DM is usually an abstract and immeasurable goal. Hence, a hierarchical analysis of criteria may be employed to break down the objectives into different levels or degrees in order to reach clearly measurable criteria (Levy et al. 2000). To simplify the explanation for the preference elicitation model developed in this paper, all of the criteria are assumed to be at the lowest level.

## 2.2 Identification of Actions

Actions are different from options in this model. The main distinction is that an action is directly or closely related with each criterion, sometimes more than one criterion, and can be interpreted as a sub-objective that satisfies a specific criterion or a set of criteria, while an option is more compressed, and formed by different combinations of actions. Therefore, the set of actions is generated based on each criterion and the background information of the modeled conflict. Since additional actions will not affect the final ranking result, all those actions that are unrelated with the options will automatically be eliminated during the evaluation calculations. Let $A = \{a_1, a_2, ..., a_k\}$ and $O = \{o_1, o_2, ..., o_n\}$ represent the set of actions and options, respectively, where $k$ is the number of actions and $n$ is the number of options.

## 2.3 Construction of the Three-layer Relationship Structure

Figure 2 graphically portrays how the three-layer relationship structure connecting preference criteria via actions to options is constructed. Three sets of variables are put together to build a three-layer structure where each node stands for an element in the corresponding set and the arcs represent the relationships among them. From left to right, the order of the layers is criterion layer, action layer and option layer. Something worth mentioning is that DMs may not agree to common sets of criteria and actions. If that is the case, different three-layer structures may be built for each DM separately.

The construction of the relationships between criteria and actions is not difficult, because an action is a sub-criterion from the criteria's point of view. The identification of each action is based on its relationship with criteria. On the other hand, from the option layer's viewpoint, an action can be treated as a "sub-option". An action may not exist independently in the real world, but it is a direct solution to its corresponding criterion or criteria. Let *CA* denote the set of relationships between the criterion and action layers, which includes all ordered pairs of elements from *C* and *A*, i.e. *C*H*A*, and *AO* stand for the set of relationships between the action and option layers, i.e. *A*H*O*.

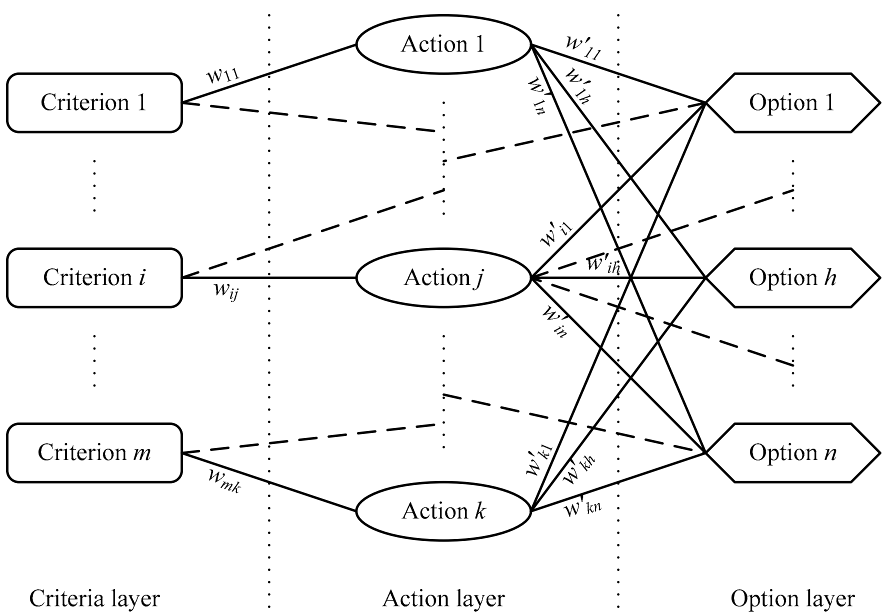


**Figure 2** Construction of the three-layer relationship structure

The importance of the various relationships is reflected by the weights determined according to a specific DM's viewpoint. In particular, for each $c_i a_j \in CA$, a normalized weight denoted by $w_{ij}$ is assigned such that (Figueira & Roy 2002):

$$\sum_{j=1}^{k} w_{ij} = 1,$$

where $0 \le w_{ij} \le 1$.

Similarly, normalized weights are also assigned to the relationships between actions and options. For each $a_j o_h \in AO$, a weight $w'_{jh}$ ($0 \le w'_{jh} \le 1$) is assigned such that:

$$\sum_{h=1}^{n} w'_{jh} = 1.$$

Note that some of the weights $w_{ij}$ ($w'_{jh}$) may be zero, which means no relationship exists between the corresponding criterion *i* and action *j* (action *j* and option *h*), but not negative, which means no action (option) can contribute negatively to the criterion (action). Examples and further explanation are given in the case study section.

## 2.4 Synthesis of the Evaluation Matrix

For each criterion, the evaluation of each alternative value in the evaluation matrix is calculated using a linear relationship. States are the combinations of options which are either selected or not selected, as is done in GMCR. Let $S = \{s_1, s_2, ..., s_l\}$ represent the set of states, where $l$ is the number of states. Thus, the corresponding evaluation of a certain state $s_t$ corresponding to criterion $c_i$ is calculated as follows:

$$W_{it} = \sum_{j=1}^{k} \sum_{h=1}^{n} w_{ij} w'_{jh} e_{ht},$$

where:

$e_{ht}$: $e_{ht} = 1$ means option *h* is selected in state *t*; otherwise, $e_{ht} = 0$;

$w_{ij}$: the weight between criterion $c_i$ and action $a_j$;

$w'_{jh}$: the weight between action $a_j$ and option $o_h$;

$1 \le i \le m$ and $1 \le t \le l$.

The calculated value, $W_{it}$, represents the value of each state corresponding to every criterion, which constitutes each entry for an $m \times l$ matrix. This specific matrix, denoted by $W^{EM}$, is called the evaluation matrix. A general format of this specific matrix is depicted as:

$$W^{EM} = \begin{array}{c} \\ c_1 \\ \vdots \\ c_i \\ \vdots \\ c_m \end{array} \begin{array}{c} \begin{array}{ccccc} s_1 & \cdots & s_t & \cdots & s_l \end{array} \\ \begin{pmatrix} W_{11} & \cdots & W_{1t} & \cdots & W_{1l} \\ \vdots & & \vdots & & \vdots \\ W_{i1} & \cdots & W_{it} & \cdots & W_{il} \\ \vdots & & \vdots & & \vdots \\ W_{m1} & \cdots & W_{mt} & \cdots & W_{ml} \end{pmatrix} \end{array}.$$

## 2.5 Calculation of the Relative Preference Ranking

After obtaining the evaluation matrix, a fuzzy MCDA methodology (De & Hipel 1987) based on ELECTRE III (Roy 1978) is used to calculate the preference ranking, whereby states are ranked from most to least preferred for each DM and ties are allowed. Fuzzy set theory was first introduced by Zadeh (1965, 1973) and has subsequently become a highly popular technique for modeling uncertainty in many disciplines. Integrating a fuzzy approach into the procedure of preference ranking permits this methodology to handle both quantitative and non-quantitative criteria in the presence of uncertainty.

As shown in Figure 3, the basic element of this methodology is a pseudo-criterion, which is identified based on the definitions of the indifference threshold. The indifference threshold, $q_i$, indicates indifference between two alternatives. The preference threshold, $p_i$ ($p_i \geq q_i \geq 0$), is used to "justify the preference in favor of one of the two alternatives (Figueira et al. 2005)". Pseudo-criterion is one of the four forms of criteria considered when constructing preference relations in decision theory (De & Hipel 1987). Using pseudo-criteria instead of true-criteria is a novelty of the ELECTRE III method (Figueira et al. 2005).

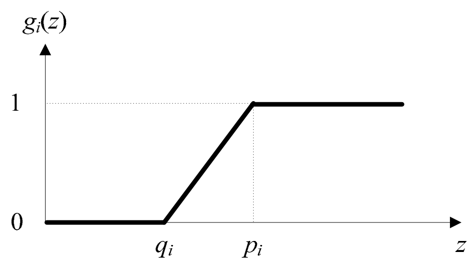


**Figure 3** Pseudo-criterion

Let $f_i(a) = W_{ia}$ and $f_i(b) = W_{ib}$ denote the corresponding evaluation of states $s_a$ and $s_b$, respectively, for a certain criterion $i$. Then, the fuzzy preference relation $a\mathrm{P}_i b$ is represented by:

$$a\mathrm{P}_i b = \begin{cases} 0, & \text{if } f_i(a) \leq f_i(b) \\ g_i(z), & \text{if } f_i(a) > f_i(b) \end{cases},$$

where $g_i(z) = g_i\left[f_i(a) - f_i(b)\right]$.

Then, a pseudo-criterion is defined as:

$$g_i(z) = \begin{cases} 0, & 0 \leq z \leq q_i \\ (z - q_i)/p_i, & q_i < z \leq (q_i + p_i) \\ 1, & z > (q_i + p_i) \end{cases}.$$

Alternatives $a$ and $b$ are indifferent when $[f_i(a) - f_i(b)]$ is smaller than $q_i$. The preference then increases gradually until $[f_i(a) - f_i(b)]$ equals $(q_i + p_i)$ and the preference becomes absolute if $[f_i(a) - f_i(b)] \geq (q_i + p_i)$.

By employing this pseudo-criterion definition, the preference matrix for all states and criteria can then be constructed. The preference matrix contains the pairwise fuzzy preference relationship information, which is derived from the evaluation matrix introduced earlier. For a certain criterion $i$, the preference matrix, denoted by $P_i^M$, can be depicted as:

$$P_i^M = \begin{matrix} s_1 \\ \vdots \\ s_a \\ \vdots \\ s_b \\ \vdots \\ s_l \end{matrix} \overset{\begin{matrix} s_1 & \cdots & s_a & \cdots & s_b & \cdots & s_l \end{matrix}}{\begin{pmatrix} 1\mathrm{P}_i1 & \dots & 1\mathrm{P}_ia & \dots & 1\mathrm{P}_ib & \dots & 1\mathrm{P}_il \\ \vdots & & \vdots & & \vdots & & \vdots \\ a\mathrm{P}_i1 & \dots & a\mathrm{P}_ia & \dots & a\mathrm{P}_ib & \dots & a\mathrm{P}_il \\ \vdots & & \vdots & & \vdots & & \vdots \\ b\mathrm{P}_i1 & \dots & b\mathrm{P}_ia & \dots & b\mathrm{P}_ib & \dots & b\mathrm{P}_il \\ \vdots & & \vdots & & \vdots & & \vdots \\ l\mathrm{P}_i1 & \dots & l\mathrm{P}_ia & \dots & l\mathrm{P}_ib & \dots & g\mathrm{P}_il \end{pmatrix}}.$$

The next step, called aggregation of the preferences, is to measure the degree of preference allotted to one alternative over another considering the integrated view of the set of criteria. In order to reflect the weights or the importance of each criterion from a DM's point of view, a normalized weight, $\overline{w}_i$, is assigned to each criterion such that:

$$\sum_{i=1}^{m} \overline{w}_i = 1, \quad \overline{w}_i \leq 1.$$

Then, for every criterion, $c_i \in C$, the concordance-discordance index can be achieved by calculating two fuzzy relationships: fuzzy preference, $a\mathrm{P}_i b$, and fuzzy doubt, $a\mathrm{d}_i b$.

The concordance relation, $a\mathrm{C}b$, represents the aggregated preference relation over all criteria. It can be calculated as the weighted sum of the preference degree $a\mathrm{P}_i b$.

$$a\mathrm{C}b = \sum_{i=1}^{m} \overline{w}_i \,.\, a\mathrm{P}_i b.$$

When all criteria have the same importance, i.e., $\overline{w}_1 = \overline{w}_2 = ... = \overline{w}_m$, the concordance relation is:

$$a\mathrm{C}b = \frac{1}{m}\sum_{i=1}^{m} a\mathrm{P}_i b \ .$$

By employing a veto-threshold as suggested by Roy (1978), the discordance index is calculated as:

(a) $a\mathrm{d}_i b =$

$$\left\langle \mathrm{Min}\left[1, \left\{\mathrm{Max}(0, \frac{f_i(b) - f_i(a) - p_i[f_i(a)]}{v_i[f_i(a)] - p_i[f_i(a)]})\right\}\right]\right\rangle,$$

when $v_i[f_i(a)] - p_i[f_i(a)] > 0$;

(b) $a\mathrm{d}_i b = 1$, when $v_i[f_i(a)] - p_i[f_i(a)] = 0$;

where $p_i$ is the preference threshold and $v_i$ is the veto threshold ($v_i \geq p_i \geq 0$), which expresses the power attributed to a given criterion to be against the assertion 'a outranks b', when the difference of the evaluation between $g_i(b)$ and $g_i(a)$ is greater than this threshold (Figueira et al. 2005). This formula has been investigated by Xu & Chen (2008) in detail.

Then, the aggregation of the discordance index forms a global doubt index via a fuzzy logical operation given as:

$$a\mathrm{D}b = 1 - \prod_{i=1}^{m}(1 - a\mathrm{d}_i b) \ .$$

A final outranking relationship, $aRb$, obtained from the conjugation of both concordance and discordance relations, can be used to demonstrate that alternative $a$ is at least as good as alternative $b$, and does not cause any serious doubt towards the preference of $a$ over $b$, with respect to every criterion.

(a) $a\mathrm{R}b = a\mathrm{C}b$, when $a\mathrm{d}_i b \leq a\mathrm{C}b$ for $i$ = 1, 2, …,$m$;

(b) $a\mathrm{R}b = a\mathrm{C}b \cdot \left\{\prod_{i^*} \frac{1 - a\mathrm{d}_i b}{1 - a\mathrm{C}b}\right\}$, for $i^*$ = set of all $i$ where $a\mathrm{d}_i b > a\mathrm{C}b$.

Finally, the "net flow" for each state or alternative considered in the preference ranking is calculated by the equation $\Phi(a) = \sum_{k\in S} aRk - \sum_{k\in S} kRa$. Identical to the last step of another MCDA approach, the PROMÉTHÉE II method (Brans 1982, Brans & Vincke 1985, Brans et al. 1986), this exploitation procedure is used to derive the complete ranking of the alternatives. The state or alternative with the highest $\Phi(a)$ value will rank first.

### 2.6 Output of Preference Information

Decision aid processes are never sequential, and hence, different phases in a model can be revised and recalculated. Therefore, the ranking results should be interpreted for meaning and compared to the actual situation in the real world. One can carry out a sensitivity analysis by changing the weights and the assignment of relationships between the different layers or parameters in the ELECTRE algorithm (for example: indifference threshold and preference threshold). The new input information is then used to recalculate the preference ranking. Iterations may be needed in order to achieve a stable or satisfactory ranking result. Then, the preference information for a DM is ready for being inputted into GMCR II to carry out the stability analysis.

## 3. Case Study: North Battleford Water Supply System Crisis

The city of North Battleford has about 14,000 residents and is located in western Saskatchewan, Canada. It is believed that a microscopic parasite, cryptosporidium, entered the water system through a water treatment filter that malfunctioned between March 21 and April 17 of 2001, after a routine maintenance of a chemical filter which was done on March 20, 2001 (Hrudey 2006). On April 25, an advisory to boil water was issued and subsequently upgraded to an order two days later. This order continued for about three months and was eventually revoked on July 25. Thousands of residents suffered from vomiting, diarrhea, and high fever due to the contamination. The parasite that caused this contamination was cryptosporidium, which is a microscopic, single-cell parasite that is about 20 times smaller than the width of a human hair. In water, it lives in a round egg called an "oocyst" that is highly resistant to cold and moist conditions. Because of the oocyst, cryptosporidium can survive in water for months, which means people who drink water contaminated with the parasite may still be sick months after the parasite first entered the water source (Laing 2002). An inquiry was held and provided the commission with a broad mandate to explore any and all circumstances leading to the outbreak of illness in North Battleford. Part of the problem is that the city's sewage treatment plant is only 3.5 kilometers upstream from its water plant. Other causes include budget cuts by both the federal and provincial governments, bad management, and inefficient regulations (Fu 2003, De et al. 2002).

In order to analyze this crisis strategically, a graph model containing three groups of DMs can be developed (Table 1). The left column in Table 1 provides the name of each DM followed by a list of options under its control. The right column furnishes descriptions of the DMs and their options.

**Table 1** Sample States in the conflict model of North Battleford water crisis

| DMs and Options | Descriptions |
|---|---|
| Residents | Victims of this crisis. |
| 1. Settle | Settle this dispute out of court. |
| 2. Sue | Sue the Federal and Provincial Governments. |
| Governments | Federal and Provincial Governments. |
| 3.Modify Regulations | Apply new regulations rather than just guidelines for water treatment plants. |
| 4. Compensation | Offer compensation to victims. |
| 5. Bigger Budget | Increase the budget for the water supply system including constructing a new sewage treatment plant and providing more training for operators. |
| Municipalities | Owner of water systems, including drinking water and sewage. |
| 6. New Sewage Plant | Construct a new sewage plant at a different site. |
| 7.Improve Management | Improve management of both water and sewage treatment. |

After entering all of this modeling information into GMCR II, three types of infeasible states are removed: 1) option 1 and 2 are mutually exclusive, because it is impossible for *Residents* to settle the dispute and sue the *Municipalities* and *Governments* at the same time; 2) at least one out of option 1 and 2 should be chosen by *Residents* since they will definitely act against the contamination; and 3) option 6 cannot be chosen without option 5 since *Municipalities* cannot construct a new sewage plant without getting extra budget from the upper levels of government. After the elimination of infeasible states, 48 feasible states are retained in this model. Once the feasible states are obtained, the next step is the calculation of the relative ranking of states. The following sections explain the procedure of generating the relative ranking of states for one of the DMs, *Residents*, by implementing the three-layer hierarchical analysis model for relative preferences presented in Section 2.

### 3.1 Determination of Criteria and Actions

*Residents* are the victims of the North Battleford drinking water tragedy, and, thus, their major concerns are obtaining compensation and ensuring the safety of drinking water in the future. According to the background research, four criteria are identified for *Residents*: 1) *Minimize operation and maintenance risks*; 2) *Minimize facilities and equipment risks*; 3) *Maximize water quality*; and 4) *Maximize compensation*.

For the action identification, because only half of the employees operating the water treatment plants had the appropriate certification, *Residents* are likely to attribute employees' inadequate training to bad management issues in this drinking water tragedy. Thus, action *More training* becomes one of the top actions that satisfy the criterion *Minimize operation and maintenance risk*. Similarly, a total of eight *Residents*' actions are established: 1) *More training*, 2) *Improvement of maintenance*, 3) *Improvement of standards*, 4) *Improvement of facilities in the water plant*, 5) *Improvement of facilities at the sewage treatment plant*, 6) *Clean source water*, 7) *Compensation*, and 8) *Solve the problem peacefully*.

### 3.2 Construction of the Three-Layer Relation Structure

In the three-layer model, the relationships between the criterion and action layers naturally exist because each action corresponds to a specific criterion in the action definition procedure. These relationships are then extended to the option level.

From the viewpoint of *Residents*, both budget cuts from the federal and provincial governments and the bad municipal management cause the poor training of employees of the North Battleford water system. Hence, both options of *Bigger budget* and *Improvement of management* are attributable to the action *More training*. The overall relationships are shown in Figure 4.

After the construction of these relationships, a normalized weight is assigned to each relationship to represent the importance or the interests of the DM under study. For example, from the viewpoint of *Residents*, both options *Bigger budget* and *Improvement of management* are equally attributable to the action *More training*. Thus, a weight of 0.5 is assigned to both relationships. All the assigned weights for criterion-action and action-option layers are shown in Tables 2 and 3, respectively.

As mentioned in Section 2.3, options may only have relationships with some rather than all actions. When there is no connection between the particular option and action, a weight of zero is assigned. For example, the option of *Regulations* (O3) only connects to the action of *Improve Standards* and has no relationships with the other two actions.

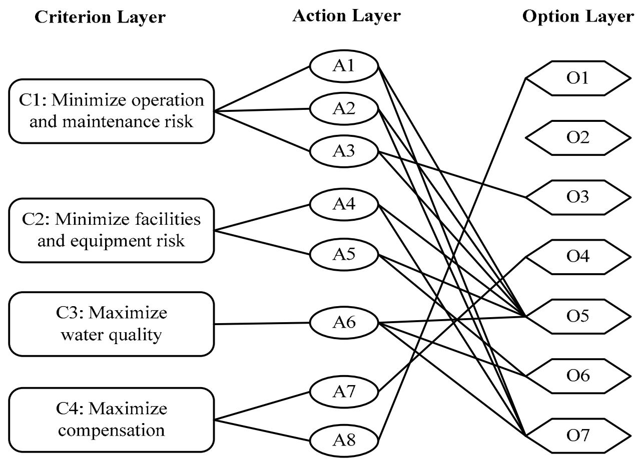


**Figure 4** Overall relationships in the hierarchical analytical model for residents

**Table 2** Weights for the criterion-action layer

| Criteria | Actions | Weights |
|---|---|---|
| C1: Minimize operation and maintenance risks | A1: More training | 0.5 |
| | A2: Improvement of maintenance | 0.3 |
| | A3: Improvement of standards | 0.2 |
| C2: Minimize facilities and equipment risks | A4: Improvement of facilities at water plant | 0.2 |
| | A5: Improvement of facilities at sewage treatment plant | 0.8 |
| C3: Maximize water quality | A6: Clean source water | 1 |
| C4: Maximize compensation | A7: Compensation | 0.8 |
| | A8: Solve the problem peacefully | 0.2 |

In practice, many different methods can be used to determine the weights. For example, one could carry out a survey or have meetings with experts to ascertain the weights. However, our main purpose here is to present the approach and to demonstrate how the methodology could be employed practically. Therefore, we examined relevant literature regarding the conflict under

**Table 3** Weights for the action-option layer

| Actions | Options | Weights |
|---|---|---|
| A1: More training | O5: Bigger budget | 0.5 |
| | O7: Improvement of management | 0.5 |
| A2: Improvement of maintenance | O5: Bigger budget | 0.2 |
| | O7: Improvement of management | 0.8 |
| A3: Improvement of standards | O5: Bigger budget | 0.2 |
| | O3: Modification of regulations | 0.8 |
| A4: Improvement of facilities at water plant | O5: Bigger budget | 0.9 |
| | O7: Improvement of management | 0.1 |
| A5: Improvement of facilities at sewage treatment plant | O5: Bigger budget | 0.5 |
| | O6: New sewage plant | 0.5 |
| A6: Clean source water | O5: Bigger budget | 0.2 |
| | O6: New sewage plant | 0.5 |
| | O7: Improvement of management | 0.3 |
| A7: Compensation | O4: Compensation | 1 |
| A8: Solve the problem peacefully | O1: Settle | 1 |

study and obtained each DM's preferences, thereby being able to calculate the overall weight for a given state and DM.

### 3.3 Synthesis of the Evaluation Matrix

Figure 5 depicts the procedure for the construction of the evaluation matrix, for the first criterion, *Minimize operation and maintenance risk*, and its hierarchical relationships with states via the action and option levels, as well as the relevant weights. A certain state contains a series of selection profiles, which is characterized by the combinations of "N" and "Y" against options, where an "N" indicates that a corresponding option is not chosen and a "Y" indicates that the option is selected.

For each criterion, each entry in the evaluation matrix can be determined by a linear aggregation method, as explained previously in Section 2. For example, the entry of state 33 for *Residents* can be calculated as: 0.3 × (0.5 × 1 + 0.5 × 1) + 0.5 × (0.2 × 1 + 0.8 × 1) + 0.2 × (0.8 × 0 + 0.2 × 1) = 0.84.

### 3.4 Calculation of the Relative Ranking of States

Based on this evaluation matrix, the calculation of state ranking is ready to be carried out. In this case study, indifference, preference and veto thresholds are set to be 0.03, 0.25 and 0.5, respectively.

As explained in Section 2, the fuzzy preference relation, $a\mathrm{P}_i b$, is firstly calculated by the pairwise comparison of two states' evaluation values. Then, the weighted sum of the preference degree, the concordance relation, $a\mathrm{C}b$, is accordingly obtained. Additionally, the discordance index $a\mathrm{d}_i b$ and corresponding aggregation are also computed by comparing the evaluations of two states and employing a fuzzy operation.

Through the computation of $a\mathrm{C}b$ and $a\mathrm{d}_i b$, the outranking relation, $a\mathrm{R}b$, is attained, and, thus, the overall preference evaluation value $\Phi$ is finalized. Table 4 provides the final

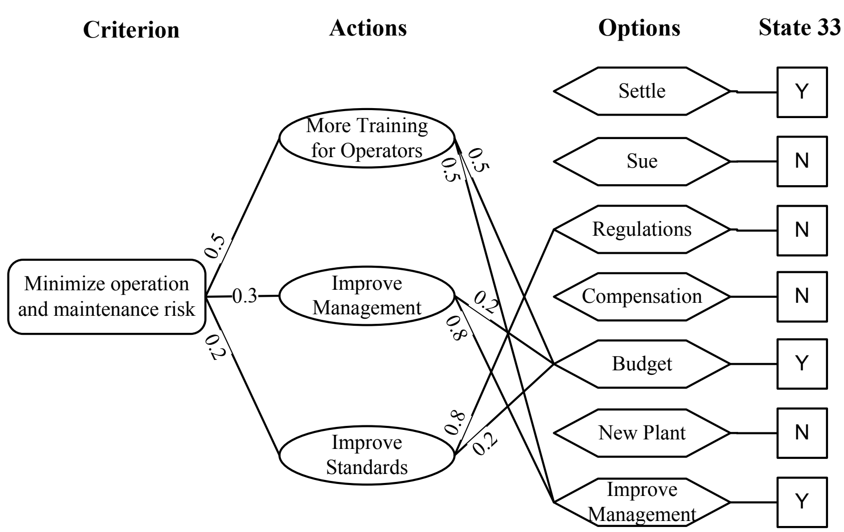


**Figure 5** Assigned weights associated with criterion 1 for *Residents*

preference values of states for *Residents*. In a similar way, other DMs' preferences can also be separately obtained. This preference information is also illustrated in Table 4.

If required, the relative preferences could be fine-tuned by examining the situation in the real world. However, the authors believe that they have a reasonable representation of the real preferences based upon their careful review of the literature. In a given application, sensitivity analyses could be carried out by changing weights and assignments of relationships between different layers or parameters for ELECTRE, such as indifference, preference, and/or veto thresholds.

**Table 4** Relative preference information

| States | Residents | Governments | Municipalities |
|---|---|---|---|
| 1 | –25.52 | –14.42 | –10.74 |
| 2 | –27.22 | –25.92 | –22.74 |
| 3 | –24.98 | –14.42 | –6.16 |
| 4 | –26.68 | –25.92 | –13.16 |
| 5 | –13.68 | –9.88 | –9.42 |
| 6 | –15.38 | –19.98 | –16.92 |
| 7 | –13.32 | –9.13 | –5.28 |
| 8 | –15.02 | –19.98 | –9.78 |
| 9 | –12.14 | –12.10 | –7.74 |
| 10 | –16.64 | –25.58 | –17.76 |
| 11 | –9.69 | –12.10 | 9.58 |
| 12 | –14.55 | –25.58 | –5.82 |
| 13 | –0.27 | –2.88 | –7.02 |
| 14 | –2.18 | –19.82 | –13.53 |
| 15 | 2.22 | –2.88 | 11.09 |
| 16 | 0.31 | –19.82 | –0.35 |
| 17 | 0.82 | 1.24 | –3.12 |
| 18 | –6.07 | –15.20 | –7.38 |
| 19 | 4.27 | 1.70 | 18.52 |
| 20 | –4.99 | –15.20 | 0.72 |
| 21 | 12.42 | 13.34 | –2.76 |
| 22 | 10.58 | –5.46 | –5.64 |
| 23 | 18.40 | 13.34 | 20.15 |
| 24 | 16.49 | –5.46 | 6.61 |
| 25 | –12.66 | 15.24 | –9.42 |
| 26 | –16.60 | –12.34 | –20.10 |
| 27 | –9.50 | 15.24 | –2.58 |
| 28 | –13.43 | –12.34 | –5.58 |
| 29 | –1.13 | 22.88 | –8.10 |
| 30 | –3.24 | -0.47 | –14.94 |
| 31 | 0.88 | 22.88 | –2.14 |
| 32 | –0.96 | –0.47 | –4.14 |
| 33 | 3.08 | 16.26 | 4.74 |
| 34 | –6.46 | –11.70 | –9.21 |
| 35 | 4.30 | 16.26 | 20.06 |
| 36 | –5.68 | –11.70 | 2.17 |
| 37 | 17.84 | 23.57 | 6.15 |
| 38 | 15.80 | 0.52 | –4.21 |
| 39 | 19.24 | 23.57 | 21.66 |
| 40 | 17.20 | 0.52 | 8.15 |
| 41 | 13.64 | 30.82 | 12.70 |
| 42 | –1.73 | –3.26 | –1.15 |
| 43 | 14.73 | 30.82 | 32.20 |
| 44 | –1.34 | –3.26 | 6.17 |
| 45 | 33.42 | 38.38 | 13.99 |
| 46 | 31.04 | 14.42 | 3.43 |
| 47 | 35.08 | 38.38 | 34.16 |
| 48 | 32.70 | 14.42 | 14.64 |

### 3.5 Stability Analysis

After the hierarchical analysis approach is used to obtain preference rankings of states for each DM in the conflict model, the ranking results serve as input into GMCR II and the stability of every state for each DM can be calculated by running GMCR II.

When a state is stable according to a specific solution concept for all DMs in a conflict, the state constitutes an equilibrium for that solution concept. This implies that no DM has the incentive to move away from that state. Table 5 lists the four strong equilibria which are stable for most solution concepts. All of these equilibria indicate three commonalities: 1) this dispute will be settled out of court; 2) *Governments* will provide compensation to the victims; 3) management will be improved in order to prevent this kind of incident from happening again in the future.

### 3.6 Further Extensions

As one of the most important research topics in GMCR, status quo analysis is used to track the moves and countermoves of conflict problems starting from the status quo, passing through transitional states, and finally, reaching one or more outcomes or equilibria (Li 2003, Li et al. 2005). In the North Battleford water crisis, the status quo at the time of the analysis is state 2, in which *Residents* launch a lawsuit against *Governments* and *Municipalities* over the incidents. Table 6 illustrates the conflict process from the state on the left via two transitional states to the outcome. As can be seen, the evolution of the conflict starts at the status quo state 2, and moves to state 16, when *Governments* decide to provide compensation, modify related regulations, and provide a bigger budget, as shown by the arrow linking states 2 and 16. In the meantime, *Municipalities* also carry out actions in improving the management and building a new sewage plant, which lead the dispute to state 48. Finally, in response to these two parties' moves, *Residents* decide to drop the case and have the suit settled, which is the actual outcome of this crisis.

**Table 5** Equilibria for the North Battleford water supply system crisis

| | | | | |
|---|---|---|---|---|
| Residents | | | | |
| 1. Settle | Y | Y | Y | Y |
| 2. Sue | N | N | N | N |
| Governments | | | | |
| 3. Modify regulations | N | Y | N | Y |
| 4. Compensation | Y | Y | Y | Y |
| 5. Bigger budget | N | N | Y | Y |
| Municipalities | | | | |
| 6. New sewage plant | N | N | Y | Y |
| 7. Improve management | Y | Y | Y | Y |
| Equilibria | 29 | 31 | 45 | 47 |

**Table 6** States transitions from the status quo via two transition states to the final outcome

| | | | | |
|---|---|---|---|---|
| Residents | | | | |
| 1. Settle | N | N | N | → Y |
| 2. Sue | Y | Y | Y | → N |
| Governments | | | | |
| 3. Modify regulations | N | → Y | Y | Y |
| 4. Compensation | N | → Y | Y | Y |
| 5. Bigger budget | N | → Y | Y | Y |
| Municipalities | | | | |
| 6. New sewage plant | N | N | → Y | Y |
| 7. Improve management | N | N | → Y | Y |
| Equilibria | 2 | 16 | 48 | 47 |

Notice that this process is exactly what occurred after the outbreak of illness. In May 2001, a public inquiry was launched into investigating the matters relating to the safety of public drinking water in the City of North Battleford. Released at the end of March 2002, the Report of the Commission of Inquiry made 61 findings and 28 recommendations (Laing 2002). In April 2002, in response to the report, the Government of Saskatchewan released a Long-Term Safe Drinking Water Strategy (LTSDWS), which outlines the province's plans to meet the need for a safe and clean drinking water supply and to protect and conserve future water supplies (Government of Saskatchewan 2002). In June 2001, the Governments of Canada and Saskatchewan announced a funding of "$500,000 to the City of North Battleford to install an Ultra Violet disinfection unit into the city's water treatment system at the F.E. Holliday Water Treatment Plant, and the City of North Battleford would provide the remaining funding of $526,480" (Western Economic Diversification Canada 2001). A new sewage treatment plant for the city was constructed downstream of both the existing water purification and sewage treatment plants (Warick 2008, Keewatin publications 2009). In the year 2003, the Province and the City reached two out-of-court settlements with approximately 800 claimants who suffered various illnesses caused by the North Battleford water contamination incident. As stated by the Government of Saskatchewan (2003), "The total value of the compensation package is approximately $425,000 which includes compensation for pain and suffering, lost income, out-of-pocket expenses and legal fees." In April 2007, Canada's New Government and the Province of Saskatchewan announced that, through the Municipal Rural Infrastructure Fund (MRIF), the City of North Battleford would receive $1 million to "expand the capacity of its ground water treatment plant and upgrade roads in eight communities" (Western Economic Diversification Canada 2007).

## 4. Conclusions

Relative preferences constitute the most important information required for modeling a strategic conflict using the Graph Model for Conflict Resolution. A hierarchical preference analysis procedure is presented in this paper to enrich preference ranking approaches embedded in the decision support system of GMCR II. An extra action layer is introduced into the hierarchical analysis methodology and serves as a bridge for users to disclose the relationships between criteria and alternatives or states. Thus, the three-layer structure provides a solid platform for aggregating option weighting with ELECTRE-based methodologies to form a criterion-oriented preference ranking technique, which can readily handle both quantitative and qualitative information.

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