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PROMETHEE with Precedence Order in the Criteria (PPOC) as a New Group Decision Making Aid: An Application in Urban Water Supply Management

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Abstract In this paper, a new group Multi-Criteria-Decision-Making (MCDM) method is introduced by combining two "Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE)" and "Multi-attribute decision making with dominance in the criteria" methods. PROMETHEE family of outranking methods is among the recently developed MCDM methods which have received lots of attention in the recent years because of its capacity in ranking finite set of alternative actions based on conflicting criteria. The second method helps the decision makers to consider ambiguity and imprecision of relative importance of each objective (criterion) without allocating importance weights to them. The proposed method of PROMETHEE with Precedence Order in the Criteria (PPOC) not only can address capabilities of PROMETHEE method just with determination of precedence order of criteria, but also can make it possible to have a group decision making environment with conflicting objectives. Operational management of an urban water supply system is a good example of a set of decision making problems with several objectives and Decision Makers (DMs). In this paper, PPOC method has been applied to the case study of Melbourne water supply system, previously analyzed in the literature, to assess a number of operation rules with respect to eight criteria evaluated under single or group decision-making situations. The satisfaction degree of each DM and the overall group ranking results have also been provided in the paper. The proposed method is applicable for different decision making problems in urban water supply management.

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1 Introduction

From middle of the past century onwards, there has been a large number of Multi-Criteria Decision Making (MCDM) methods developed. They differ from each other in the required quality and quantity of information, the user-friendliness, the sensitivity analysis tools, and their mathematical properties. Some researchers such as Szidarovszky et al. (1986) and Dyer et al. (1992) reviewed the history of development of these methods. These techniques have become useful decision aid tools for decision makers (DMs) dealing with the growing complexity and importance of the decision making problems.

Decision making analysis is recognized as a disciplined approach for managing urban water resources systems for particular uses that require interactive dialogue among all stakeholders who have different objectives (Cai et al. 2004; Abrishamchi et al. 2005; Calizaya et al. 2010). Decision making analysis methodologies that are capable of conflict resolution are particularly useful tools in analyzing decision problems that extend to the level of accommodating the stakeholders' preferences. Conflict resolution in the context of urban water supply systems usually involves the affected stakeholders in solving the issues surrounding the dominance of one water use over another, the rights of natural systems, and the rights of water users. These facts lead to the definition of discrete and finite alternatives which can be evaluated by different criteria.

MCDM models are divided into the two classes of compensatory and non-compensatory methods. The non-compensatory models include the methods in which trade-off between the criteria is not allowable. It means that a weak point of one criterion is not recovered by the other criteria. In the compensatory models, the trade-off between the criteria is allowable which means that a change (even very small) in one criterion can be recovered by the opposite change in another criterion or other criteria and relative importance of the criteria is incorporated in the decision making process as well. Therefore, this class of MCDM models has been preferred over non-compensatory techniques for ranking of urban water supply management scenarios. Several compensatory techniques such as AHP, ELECTRE, SAW, Goal Programming, Compromise Programming, etc. have been used in previous studies related to urban water management. For example, Jaber and Mohsen (2001) used AHP method for evaluation of water supply alternatives in Jordan and Abrishamchi et al. (2005) used Compromise Programming for urban water supply management in Zahedan City in Iran. Zahraie et al. (2008) ranked the sustainable water supply and demand management scenarios in river-basin scale using ELECTRE technique. More information about different applications of MCDM models in water supply management can be found in Lai et al. (2008).

Among the various MCDM methods, two methods have been considered in this study to present a new decision making tool. PROMETHEE method (Brans et al. 1986) is one of the most widely used outranking methods which allow interactive learning. This method is based on pair-wise comparison of alternatives (separately on each criterion) and aggregating the DM preferences on each criterion. Georgopoulou et al. (1998) presented a Group Decision Support System (DSS) designed for supporting computational tasks and facilitating decision analysis in energy planning. They employed PROMETHEE outranking approach in MCDA module. Srinivasa et al. (2000) applied this method for sustainable water resources planning considering different social, environmental, and economic criteria. Simon et al. (2004, 2005) used this method to evaluate water management strategies. Raju and Kumar (2006) solved a

PROMETHEE model to select the suitable irrigation planning alternatives. Morais and Almeida (2007) applied PROMETHEE method for group decision making for leakage management in urban water distribution networks. Kodikara (2008) and Kodikara et al. (2010) evaluated a real case study to find the optimal operation rule of Melbourne water supply system by elicitation of the stakeholders' preferences and modeling them by PROMETHEE method in a group decision space. Mutikanga et al. (2011) applied PROMETHEE model as an integrated multi criteria decision aiding framework for strategic planning of water loss management Also a detailed literature review on the applications of this method can be found in Behzadian et al. (2010).

The second method which is used in this paper is a Multi-Attribute-Decision-Making (MADM) technique with dominance in the criteria which has been developed by Yakowitz and Lane (1993) and belongs to the class of compensatory MCDM models. It helps DMs to rank the alternatives with respect to the criteria utilizing a linear additive utility function. In this method, in contrary to many MCDM methods such as PROMETHEE, assignment of certain values to the weights of criteria to present the relative importance of the criteria in the decision making analysis is not necessary and only a precedence order in the set of criteria must be provided by DM and the minimum and maximum values of the additive utility function are used to find the final ranking of the alternatives. Yakowitz and Lane (1993) developed and used this method for decision making on the different farming practices.

In this study, a hybrid method of PROMETHEE with precedence order in the criteria is developed. While Merino et al. (2003) proposed fuzzy compromise programming with precedence order in the criteria and applied it for an aquifer management problem; development of PROMETHEE with precedence order in the criteria has not been reported. The proposed hybrid method can be used for various MCDM problems but it is specifically suitable for the case of urban water management because of the following reasons:

1- Both of families of PROMETHEE and MADM with precedence order in the criteria methods are compensatory methods in which the relative importance of the criteria is incorporated in the decision making process.
2- DMs are able to contribute in the decision making processes by determining parameters and thresholds in PROMETHEE model and increasing the ranking accuracy by pairwise comparison of the alternatives.
3- Since scoring procedure in PROMETHEE has a linear additive utility function form, it can be mixed with the multi-attribute decision making with dominance in the criteria method.
4- PROMETHEE has a fuzzy view toward decision making problems and therefore it has been considered a useful tool for stochastic decision making problems. It also models the decision makers' preferences in a realistic way by using pseudo-criteria.
5- Not providing complete pre-order is the major limitation of the some famous MCDM methods such as ELECTRE. The final product of methods such as ELECTRE is partial pre-order between alternatives (not containing a relative ranking of all of the alternatives) rather than a complete pre-order which makes it hard to be used in the cases like selection of the suitable urban water supply alternatives. In this study, by using PROMETHEE method, a complete pre-order can be determined.
6- Since in most of the cases, it is difficult for the DMs to provide exact values for the weights of the criteria used in MCDM applications, in the proposed hybrid method, DMs only provide precedence order of the criteria. Therefore uncertainties in the importance of the criteria and stakeholders' knowledge are somehow incorporated in the decision making process.

This paper also provides the group decision making procedure and results. The satisfaction degree of each DM with overall group ranking results are presented as well. PPOC method is applicable to the urban water management problems because they usually have diverse objectives and DMs involved in the decision making process usually have conflicting ideas. In the next sections of the paper, first the MCDM techniques with importance order of the criteria and PROMETHEE family of outranking methods are explained and then the details of the proposed PPOC method are explained. The case study of this paper is Melbourne Water Supply System (MWSS) which was studied earlier by Kodikara (2008) and Kodikara et al. (2010).

2 Methodology

The first stage in each MCDM problem is to determine the following issues:

- Identification of the decision makers and stakeholders
- Selection of the criteria and their relative weights
- Selection of the alternatives

After that, selection of a proper method to rank these alternatives is necessary. As it was mentioned before, two methods have been selected and combined in this paper. These methods have been briefly described in the following sections.

2.1 MCDM with Precedence Order of the Criteria

This method was first proposed by Yakowitz and Lane (1993) as a simple and efficient MCDM method. In this method, the utility of each alternative is calculated by the following additive utility function:

$$U_j = \sum_{i=1}^{m} w_i v_{ij} \tag{1}$$

Where m is the number of criteria considered, w_i is the weight of ith criterion (objective) assigned by the DM and v_{ij} is the normalized performance of the jth alternative based on the ith criterion. Unlike many MCDM methods, the DMs should only provide the precedence order of the criteria in this method. The fact that this method does not expect DMs to provide relative weights for the criteria makes it a suitable model for many decision making problems. DM can impose an importance order to the attributes as follows:

$$w_1 \geq w_2 \geq \ldots \geq w_m \tag{2}$$

This relation shows that criterion 1 is more important than criterion 2 and criterion 2 is more important than the rest of criteria except for the first criterion and so on. Once these precedence orders of criteria are established, the best and worst additive utility function values for each alternative are estimated based on the two following linear optimization models by maximizing or minimizing the additive utility function as the objective function,:

$$\begin{aligned} &\mathit{Maximize}\ (\mathit{or\ Minimize})\ U_j = \sum_{i=1}^{m} w_i v_{ij} \\ &\mathit{Subject\ to}:\ w_1 \geq w_2 \geq \ldots \geq w_m \\ &\qquad \sum_{i=1}^{m} w_i = 1 \\ &\qquad w_m \geq 0 \end{aligned} \tag{3}$$

Yakowitz and Lane (1993) showed that solving these two optimization problems leads to the extreme values of the additive utility function (BU_j & WU_j) shown in the following equations:

$$BU_j = Max(U_j) = \underset{k}{Max}\{S_{kj}\} \tag{4}$$

$$WU_j = Min(U_j) = \underset{k}{Min}\{S_{kj}\} \tag{5}$$

Eq. (6) assigns different sets of weights to the performances of the criteria based on the precedence order imposed by Eq. (2). If there are two criteria with equal importance based on DM's opinion (w_i=w_{i+1}), the integer value of k=i should be removed from the sets of k= 1,2,…,m in Eq. (6).

$$S_{kj} = \frac{1}{k}\sum_{i=1}^{k} v_{ij} \quad k = 1, 2, \ldots, m \tag{6}$$

For ranking the alternatives, if $BU_k \geq BU_j$ and $WU_k \geq WU_j$, alternative k dominates alternative j based on the established precedence order of the weights. In cases that solving the linear programming problem in Eq. (3) leads to partial ranking and does not yield a complete ranking of the alternatives, the following two solutions are used for ranking:

- The score of each alternative can be evaluated based on the average of best and worst additive values as follows:

$$S_j = \frac{BU_j + WU_j}{2} \tag{7}$$

- Ranking of the alternatives can be estimated based on the additional information about weights of the criteria provided by the DMs. To consider the additional information, Eq. (2) should be replace by Eq. (8).

$$w_1 \geq c_2 w_2, \quad w_2 \geq c_2 w_3, \ \ldots, \quad w_{m-1} \geq c_m w_m \geq 0 \tag{8}$$

Where c_i indicates the level of preference between the criteria. For instance, if c_2=3, criterion 2 has an importance at least triple as much as criterion 3. For eliciting the best and worst additive value functions let:

$$S_{kj} = \frac{1}{\sum_{i=1}^{k} c_i} \sum_{i=1}^{k} \frac{v_{ij}}{c_i} \prod_{r=i}^{k} c_r \tag{9}$$

Then, the extreme values can be obtained by using Eqs. (4) and (5). In this case, if two conditions of $BU_k \geq BU_j$ and $WU_k \geq WU_j$ are satisfied, it can be concluded that alternative k dominates alternative j, otherwise Eq. (7) is applied or c values are modified until complete ranking can be obtained.

2.2 PROMETHEE

The PROMETHEE family of outranking methods is one of the most recently developed MCDM methods which were proposed by Brans et al. (1986). ROMETHEE is an outranking method for a finite set of alternative actions. It often works based on conflicting criteria. PROMETHEE is also a quite simple ranking method in the concept and application compared with the other methods for multi-criteria analysis (Brans et al., 1986). The PROMETHEE family of methods includes the followings (Morais & Almeida, 2007):

- PROMETHEE I establishes a partial preorder among the alternatives and can be used for choice problems.
- PROMETHEE II establishes a complete preorder among the alternatives and can be used for ranking problems.
- PROMETHEE-GAIA (Geometrical Analysis for Interactive Aid) produces extension of the results of PROMETHEE using a visual and interactive procedure.
- PROMETHEE-GDSS provides a group decision making tool based on the PROMETHEE II method.

In this paper, two methods of PROMETHEE II and PROMETHEE-GDSS have been used for the purpose of ranking with respect to the precedence order in the criteria. The basic principle of PROMETHEE II is based on a pair-wise comparison of alternatives. Alternatives are evaluated according to different criteria, which have to be maximized or minimized. The implementation of the PROMETHEE II requires the two following additional types of information:

1- The weights of criteria: Determination of the weights is an important step in most multi-criteria methods. PROMETHEE II assumes that the decision-maker is able to weight the criteria appropriately, at least when the number of criteria is not too large (Macharis et al. 1998).
2- The preference functions: This function translates the difference between the evaluations of two alternatives into a preference degree ranging from zero to one for each criterion. To facilitate the association of a preference function to each criterion, the developers of the PROMETHEE method have proposed six types of preference functions shown in Fig. 1 which have performed satisfactorily for many real world applications. Each shape depends on up to three thresholds: (1) indifference threshold (q), (2) preference threshold (p) and (3) Gaussian threshold (s). In Fig. 1, Type I, Type II and Type III are variants of Type V.

The method, which was developed first for single DM case, consists of the following steps:

- Step1: Determination of deviations based on pair-wise comparison between each set of two alternatives *a* and *b*:

$$d_i(a,b) = g_i(a) - g_i(b) \quad j = 1,2,\ldots,m \tag{10}$$

Where $g_i(a)$ and $g_i(b)$ are the values of criterion i for alternatives a and b, respectively.

- Step2: Estimation of preference function ($P_i(a,b)$ (as shown in Fig. 1:

$$P_i(a,b) = H[d_i(a,b)] \tag{11}$$

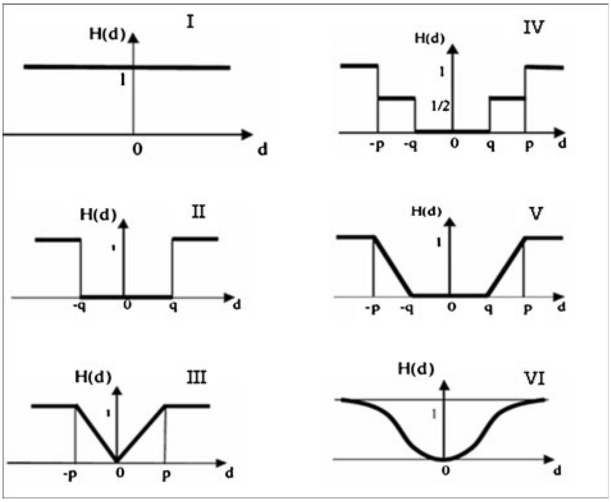

Fig. 1 Preference function types of PROMETHEE method (Brans and Vincke 1985)

- Step 3: Calculation of an overall or global preference index as follows:

$$\forall\, a, b \in A, \quad \pi(a,b) = \sum_{i=1}^{m} w_i P_i(a,b) \tag{12}$$

Where $\pi(a,b)$ varies from 0 to 1 and expresses the degree of which alternative a is preferred over b based on all the criteria (m).

- Step 4: Calculation of outranking flows/PROMETHEE I partial ranking as follows:

$$\text{the leaving flow}: \phi^{+}(a) = \frac{1}{n-1} \sum_{x=1}^{n} \pi(a,x) \tag{13}$$

$$\text{the entering flow}: \phi^{-}(a) = \frac{1}{n-1} \sum_{x=1}^{n} \pi(x,a) \tag{14}$$

Where n is the number of alternatives.

- Step 5: Calculation of net outranking flow/PROMETHEE II complete ranking as follows:

$$\text{the net flow}: \phi(a) = \phi^{+}(a) - \phi^{-}(a) \tag{15}$$

Where $\phi(a)$ denotes the net outranking flow for each alternative. Then, the following conditions are applied to the final ranking:

$$a\,P\,b \quad \textit{if} \quad \phi(a) \succ \phi(b) \quad \textit{and} \quad a\,I\,b \quad \textit{if} \quad \phi(a) = \phi(b) \tag{16}$$

Where P stands for strict preference and I stands for indifference.

Macharis et al. (1998) developed the PROMETHEE GDSS (Group Decision Support System), which is an extension of the PROMETHEE methodology with group decision-making capability. In this method, the global net flow for the whole group for a particular alternative is defined as:

$$\phi^G(a) = \sum_{r=1}^{R} w_r \phi^r(a) \tag{17}$$

Where R is the number of decision makers, $\phi^r(a)$ is the net flow of alternative a for the decision maker r with a relative power in decision making procedure denoted by w_r.

2.3 PROMETHEE with Precedence Order in the Criteria (PPOC)

In this research, a new MCDM method, namely PPOC, is developed in which the decision maker can have higher level of contribution compared with similar methods including PROMETHEE itself. The DM is not forced to provide specific values for the weights of criteria or additive utility function and this means that the only requirement for the DM contribution is to provide a precedence or importance order of the criteria. PPOC is formulated by combining PROMETHEE-II and the method developed by Yakowitz and Lane (1993). For this purpose, formulation of the net flow in PROMETHEE-II must be converted to the form of an additive utility function. For this purpose, Eqs. (13)–(15) can be rewritten as follows:

$$\phi_j^+(a) = \frac{1}{n-1} \sum_{i=1}^{m} w_i \left[\sum_{x=1}^{n} P_i(a,x) \right] \tag{18}$$

$$\phi_j^-(a) = \frac{1}{n-1} \sum_{i=1}^{m} w_i \left[\sum_{x=1}^{n} P_i(x,a) \right] \tag{19}$$

$$Net\ Flow: \quad \phi_j(a) = \frac{1}{n-1} \sum_{i=1}^{m} w_i \left[\sum_{x=1}^{n} P_i(a,x) - P_i(x,a) \right] \tag{20}$$

To address this process in the form of utility, Eq. (1) can be rewritten as:

$$U = \sum_{i=1}^{m} w_i v^*_{ij} \tag{21}$$

Where $v^*_{ij} = \frac{1}{n-1} \left[\sum_{x=1}^{n} P_i(a,x) - P_i(x,a) \right]$ and $\sum_{i=1}^{m} w_i = 1$.

The maximum and minimum values of U (or here denoted by ϕ_j) can be elicited by using Eqs. (4) and (5) as follows:

$$Max\left(\phi_j\right) = \underset{k}{Max}\{S_{kj}\} \tag{22}$$

$$Max\left(\phi_j\right) = \underset{k}{Max}\{S_{kj}\} \tag{23}$$

S_{kj} is estimated using Eq. (9), while v_{ij} is replaced by v^*_{ij}.

In this paper, Eq. (7) is applied to find the score of each alternative and then the alternatives are ranked using these scores. Eq. (17) can then be used while $\phi^r(a)$ for each DM is replaced by S_j to perform the group decision making.

2.4 Personal and Group Satisfaction Indices (PSI, GSI)

In this paper, two important indices (PSI, GSI) have been applied to estimate the individual and group satisfaction of DMs about the final ranking results. PSI can be defined as the correlation coefficient between the individual and the group rankings. For each DM, having the individual rank, R_{DM}, and the group rank, R_G, PSI for the decision maker r can be estimated using the following equation (Goletsis et al. 2003):

$$PSI_r = 1 - \frac{6\sum_{j=1}^{n} d_r^2}{n^3 - n} \tag{24}$$

Where d_r is the difference between the ranks of R_{DM} and R_G. PSI values are in the range of −1 to +1. Closer value of this index to +1 means that there is no considerable difference between two rankings and satisfaction is maximum. PSI values close to −1 means that the group rank is opposite of the individual rank and finally, PSI near zero means that group and individual rankings are different and there is no consistency between them. If the values of this index do not satisfy the stakeholders, they must revise the parameters they have assigned in the decision making process such as precedence order of the criteria.

GSI is the weighted sum of PSI_r and it shows the group satisfaction (Goletsis et al. 2003):

$$GSI = \sum_{r=1}^{R} w_r PSI_r \tag{25}$$

The main stages of the proposed methodology have been illustrated in Fig. 2.

3 Test Example

The case study of this paper is Melbourne Water Supply System (MW) which was also used by Kodikara (2008) and Kodikara et al. (2010) as a case study for group multi-objective decision making problem using PROMETHEE method. MW operates and maintains a multi-reservoir system that supplies water to a population of about 3.7 million people in the city of Melbourne. Figure 3 shows all the harvesting reservoirs, seasonal storage reservoirs, major inflows and transfers between the reservoirs. Harvesting reservoirs receive water mainly from uninhabited and forested catchments around Melbourne. Then water from the harvesting reservoirs is transferred via the seasonal transfer system (pipelines and aqueducts) primarily by gravity flows to seasonal storages that are located closer to Melbourne metropolitan area, for supplying to the three retail water companies, City West Water (CWW), South East Water (SEW) and Yarra Valley Water (YVW). It has been long recognized by the urban water industry in Australia in general and Melbourne in specific that their ability to meet future demands for water is limited because water consumption is increasing due to the growing population.

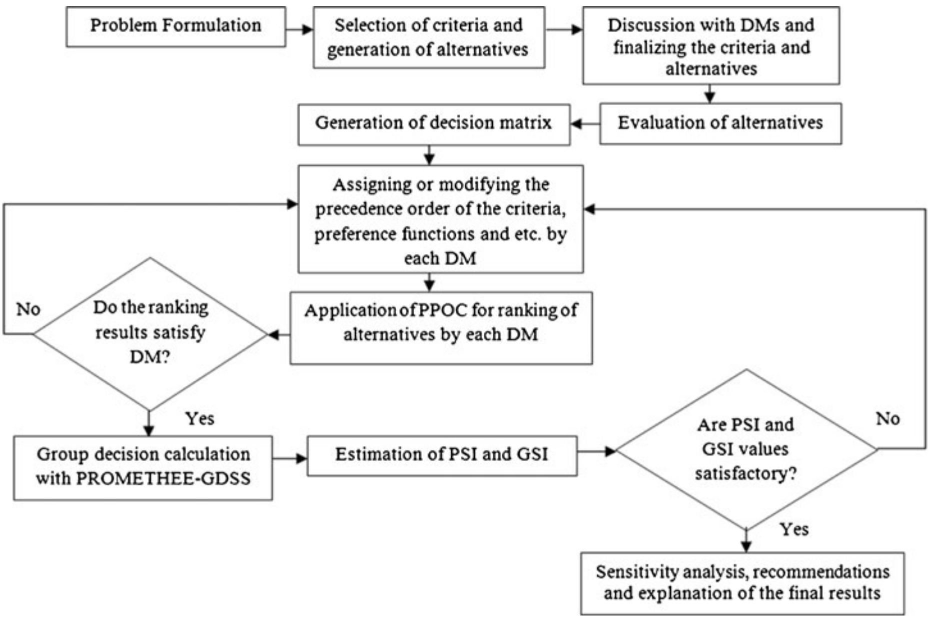

Fig. 2 Steps of using PPOC

Recent dry conditions across most of Victoria State have also aggravated the problem by highlighting the limited availability of water resources (Water Resources Strategy Committee 2001). For Melbourne, it is predicted that the water supplies could be reduced by 20 percent by 2050, and the implications of potential climate

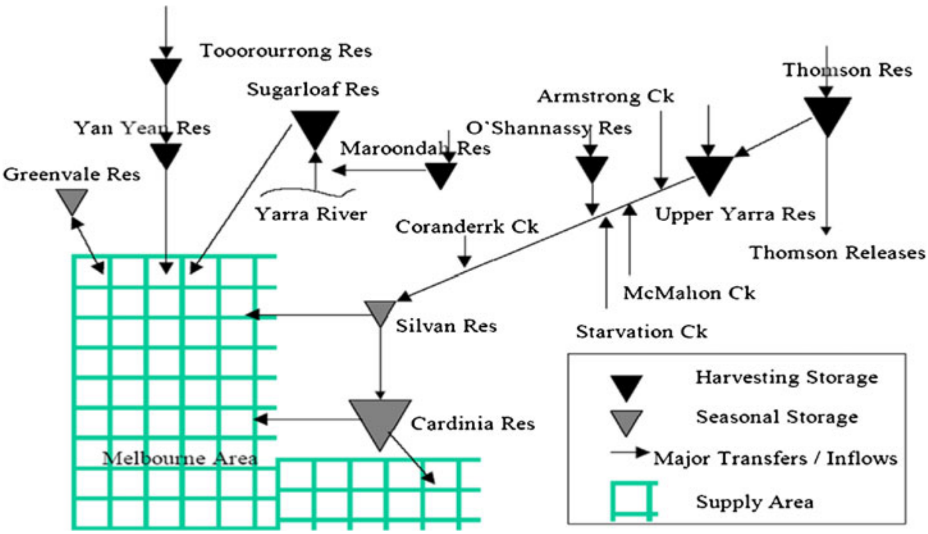

Fig. 3 Melbourne water supply system (Kodikara et al. 2010)

change for Melbourne's water resources have also been identified as (Howe et al. 2005):

- Increased average and summer temperatures
- Reduced rainfall
- Reduced stream flows, and more extreme events such as hot days, dry days, and increased rainfall intensity during storms

The Water Resources Strategy Committee for Melbourne area also identified the possible scarcity of water for Melbourne and proposed four broad options to meet the future water demands till the year 2050 (Kodikara 2008; Kodikara et al. 2010):

- Seek new water resources
- Reduce demand
- Substitute with recycled water and efficient and optimal operation of existing water supply system

This study is focused on the last option. The optimal long and short term operation of the system could be achieved through a range of options, which meet the operational objectives to different levels. The multiple facets of these operational objectives often conflict with each other, making it difficult to tentatively decide on an optimum operating rule. So to meet the objective, a proper MADM method should be applied. One of the main steps in this procedure is selection of alternatives and criteria as well as the stakeholder's preferences on these criteria.

Kodikara (2008) and Kodikara et al. (2010) identified the following four areas to generate alternative operating rules for existing MW:

- Demand restriction policy: To manage the water supplies in periods of drought, Melbourne's Drought Response Plan, developed by metropolitan water authorities can be used to reduce the water demand and consumption. This is followed by a 4-stage demand restriction policy on the total storage volume in the reservoirs.
- Pumping/treatment at Sugarloaf Reservoir: Sugarloaf Reservoir and Winneke water treatment plant are among the main parts of the Melbourne system which supply the summer peak demand and then assist in drought recovery of Thomson reservoir. This reservoir is mostly dependent on the limited volume of water pumped every year from the Maroondah aqueduct and Yarra River at Yering Gorge. This water is then fully treated at the water treatment plant to provide high quality drinking water. Generally, pumping water from Maroondah aqueduct water is preferred because it requires less-head pumping and it has higher quality of water than harvested water from the Yarra River.
- Hydropower generation at Thomson and Cardinia Reservoirs: A limited amount of hydropower is generated as a by-product at two locations, Thomson Reservoir and Cardinia Reservoir, when the water is released or transferred to meet environmental requirements or urban demands. Some rules have been defined to restrict hydropower generation in these dams. By application of these operating principles, security of Melbourne water supplement will be increased.
- Minimum passing flows in Yarra River and Thomson River: A considerable amount of water for Melbourne is supplied from Thomson and Yarra Rivers. This fact makes a decrease in downstream flows, which leads to deterioration of downstream river

Table 1 Decision matrix of alternative operating rules (Kodikara 2008)

Alternative (Operation Rule)	Restriction Policy	Pumping/ treatment at Sugarloaf Reservoir	Hydropower generation at Thomson and Cardinia Reservoirs	Minimum passing flows in Thomson and Yarra Rivers	Supply Reliability-SR (%)	Worst Restriction Level (WL)	Duration of Restrictions (DR) (months)	Frequency of Restrictions (FR)	Pumping/ Treatment Cost (PC) ($mil/year)	Hydropower Revenue (HR) ($mil/year)	River Flows (RF) (10^6 m^3/year)	Total System Minimum Storage (MS) (10^6 m^3)
1	Current	Current	Current	Current	94.2	2	32	0.022	5.2	5	531	745
2	Current	Current	Current	Variation	82.4	4	106	0.044	5.83	5.29	540	468
3	Current	Current	Variation	Current	94.7	2	32	0.022	5.13	4.88	531	783
4	Current	Current	Variation	Variation	82.6	4	106	0.044	5.79	5.27	540	469
5	Current	Variation	Current	Current	96.8	1	18	0.022	5.72	5.1	530	770
6	Current	Variation	Current	Variation	84.5	4	92	0.033	6.29	5.34	537	505
7	Current	Variation	Variation	Current	98	1	17	0.022	5.62	4.97	530	822
8	Current	Variation	Variation	Variation	84.6	4	92	0.033	6.26	5.31	536	510
9	Variation	Current	Current	Current	92.7	2	38	0.033	5.16	4.99	532	763
10	Variation	Current	Current	Variation	74.2	5	123	0.078	5.72	5.28	542	526
11	Variation	Current	Variation	Current	93.3	2	37	0.033	5.12	4.88	531	802
12	Variation	Current	Variation	Variation	75.1	5	123	0.078	5.7	5.26	542	526
13	Variation	Variation	Current	Current	93.4	2	35	0.033	5.69	5.09	531	789
14	Variation	Variation	Current	Variation	82.7	4	105	0.044	6.24	5.34	538	564
15	Variation	Variation	Variation	Current	95.2	2	33	0.022	5.61	4.97	530	835
16	Variation	Variation	Variation	Variation	83.2	4	105	0.044	6.21	5.31	538	565

Table 2 DMs' preference functions (Kodikara et al. 2010)

DMs	SR	WL	DR	FR	PC	HR	RF	MS
RM 1	Type I	Type I	Type V $q=4$ $p=8$	Type V $q=0.06$ $p=0.1$	Type V $q=1$ $p=2$	Type V $q=0.15$ $p=2.15$	Type I	Type III $p=90$
RM 2	Type III $p=5$	Type III $p=3$	Type III $p=12$	Type V $p=0.2$ $q=0.1$	Type V $q=1$ $p=5$	Type III $p=3.6$	Type III $p=80$	Type IV $q=92$ $p=184$
RM 3	Type II $q=5$	Type II $q=2$	Type II $q=12$	Type II $q=0.2$	Type I	Type II $q=1.9$	Type II $q=80$	Type II $q=39$
RM 4	Type II $q=5$	Type II $q=3$	Type II $q=12$	Type II $q=0.06$	Type II $q=2$	Type II $q=1.9$	Type II $q=30$	Type I
WU_{rep}	Type III $q=0$ $p=87.5$	Type II $q=4$ $p=4$	Type II $q=120$ $p=120$	Type II $q=1$ $p=1$	Type V $q=1.5$ $p=3$	Type V $q=0.86$ $p=2.29$	Type V $q=18.3$ $p=45$	Type V $q=208$ $p=380$
EN_{rep}	Type II $q=87.5$ $p=87.5$	Type II $q=4$ $p=4$	Type II $q=120$ $p=120$	Type II $q=1$ $p=1$	Type II $p=2$ $q=2$	Type V $q=0.85$ $p=1.7$	Type V $q=80$ $p=160$	Type II $q=621$ $p=621$

ecosystem. So some operation rules have been defined to increase the minimum passing flow. This work has two main benefits: increase of the environmental health of rivers and reduction of water consumption in the upstream.

To generate the alternative operating rules, one variation (improvement) for each of the above operation rules was considered. For example in the case of demand restriction policy, the rule curves for the operational management of the reservoirs are changed. So, sixteen alternatives have been generated based on the current state or variable operation state to minimize the risk of water shortage in the future. Moreover, eight criteria have been identified that represent the system performance with respect to these sixteen operation rules. Decision matrix (values of eight criteria for sixteen alternative operation rules) of this MCDM problem has been illustrated in Table 1.

To evaluate these sixteen alternatives based on the eight criteria in a group decision making environment, three different stakeholders have been selected:

- Resource Managers (RMs)
- Water Users (WUs)

Table 3 Normalized weights of criteria for each DM (Kodikara et al. 2010)

DMs	SR (w_1)	WL(w_2)	DR(w_3)	FR (w_4)	PC(w_5)	HR(w_6)	RF (w_7)	MS (w_8)
RM 1	0.09	0.18	0.13	0.10	0.17	0.00	0.00	0.33
RM 2	0.04	0.08	0.03	0.06	0.01	0.00	0.20	0.58
RM 3	0.11	0.14	0.12	0.09	0.25	0.11	0.00	0.18
RM 4	0.08	0.03	0.07	0.05	0.01	0.00	0.38	0.38
WU_{rep}	0.05	0.04	0.05	0.05	0.07	0.04	0.33	0.37
EN_{rep}	0.05	0.04	0.05	0.04	0.01	0.05	0.40	0.36

Table 4 Precedence orders in the case study

DMs	Precedence Order
RM 1	$w_8 \geq w_2 \geq w_5 \geq w_3 \geq w_4 \geq w_1,\ w_6 = w_7 = 0$
RM 2	$w_8 \geq w_7 \geq w_2 \geq w_4 \geq w_1 \geq w_3 \geq w_5,\ w_6 = 0$
RM 3	$w_5 \geq w_8 \geq w_2 \geq w_3 \geq w_1 = w_6 \geq w_4,\ w_7 = 0$
RM 4	$w_8 = w_7 \geq w_1 \geq w_3 \geq w_4 \geq w_2 \geq w_5,\ w_6 = 0$
WU_{rep}	$w_8 \geq w_7 \geq w_5 \geq w_3 = w_4 = w_1 \geq w_2 = w_6$
EN_{rep}	$w_7 \geq w_8 \geq w_1 = w_3 = w_6 \geq w_2 = w_4 \geq w_5$

- Environmentalists (ENs)

Kodikara (2008) tested different hypothetical group decision-making situations and then the sensitivity and robustness of the results were observed due to the varying group compositions in terms of the number of DMs in the decision group. But in this study, only one of these hypothetical groups is analyzed to evaluate capabilities of the proposed decision making aid (PPOC method). This group consists of six members (four RMs, one WU, and one EN). Preference functions for representative RMs, WU and EN are shown in Table 2 and the weights of criteria assigned by these stakeholders are shown in Table 3. In the next part of this study, results of application of PPOC method are presented.

3.1 Data Analysis and Ranking Results

In order to use PPOC method, the precedence order has been imposed in the criteria for each decision maker and then their ranking results obtained by PROMETHEE-II, are aggregated to find the group ranking of alternatives. These normalized weights in Table 3 indicate the precedence order shown in Table 4. In this table, W_i indicates the weight of ith criterion shown in Table 3. Some DMs have not considered any criteria in their decision making procedure and assigned the zero value to their weights. So the ranking calculations are done only by the remaining criteria.

After solving the MCDM problem with application of the PPOC model described in section 2.3, score of each alternative is obtained. To describe the ranking results, three scenarios were defined. In the first scenario, MADM problem has been solved based on the fixed weights of the criteria as illustrated in Table 3 (traditional PROMETHEE method). Figure 4 shows the final score (net flow) of the alternatives in the first scenario and for each stakeholder. This figure makes it possible to compare the stakeholders' opinions about each alternative. In the next phase of the analysis, second scenario has been developed based on the PROMETHEE parameters and precedence order of the criteria assigned by the

Table 5 Additional information (C-vectors)

DMs	C-Vectors
RM 1	c_1=2, c_2=1, c_3=2, c_4=1, c_5=1
RM 2	c_1=3, c_2=3, c_3=2, c_4=1, c_5=1, c_6=3
RM 3	c_1=2, c_2=2, c_3=2, c_4=1, c_5=1, c_6=1
RM 4	c_1=1, c_2=4, c_3=1, c_4=2, c_5=1, c_6=4
WU_{rep}	c_1=2, c_2=5, c_3=1, c_4=1, c_5=1, c_6=1, c_7=1
EN_{rep}	c_1=2, c_2=7, c_3=1, c_4=1, c_5=1, c_6=1, c_7=4

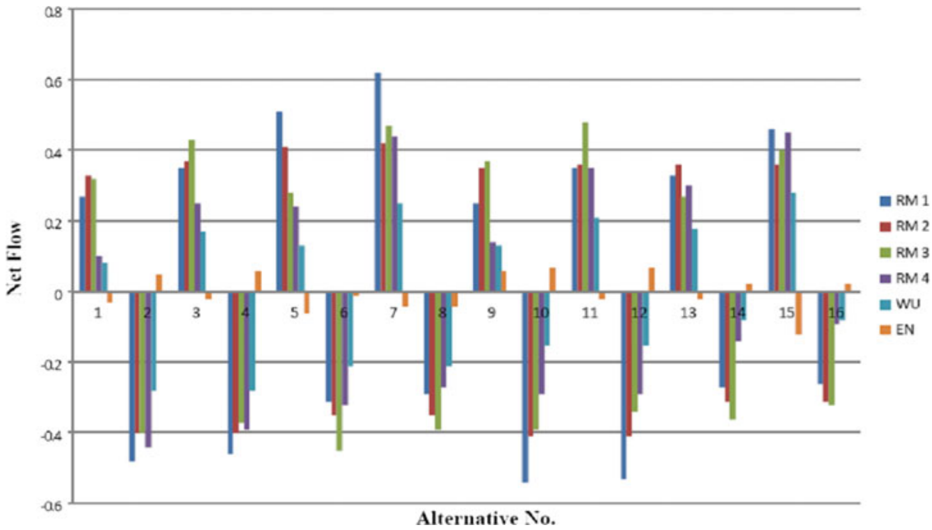

Fig. 4 Net flows of alternatives in scenario No.1

stakeholders (Table 4). It is clear that in this case, $c_2=c_3=\ldots=c_8=1$ (PPOC without additional information). Figure 5 represents the results of this scenario.

To assess the role of using additional information about the relative importance of the criteria, values of c-vectors were assigned to the criteria as additional information for each DM based on Table 3 (fixed values of weights). These values can be seen in Table 5. So, the third scenario has been defined regarding these additional information and its results are shown in Fig. 6. Finally, to obtain the group decision making results, Eq. (17) has been used when equal importance of decision makers ($w_{DM1} = w_{DM2} = \ldots = w_{DM6}$) has been considered. Figure 7 and Table 6 show the final group net flows and complete rankings

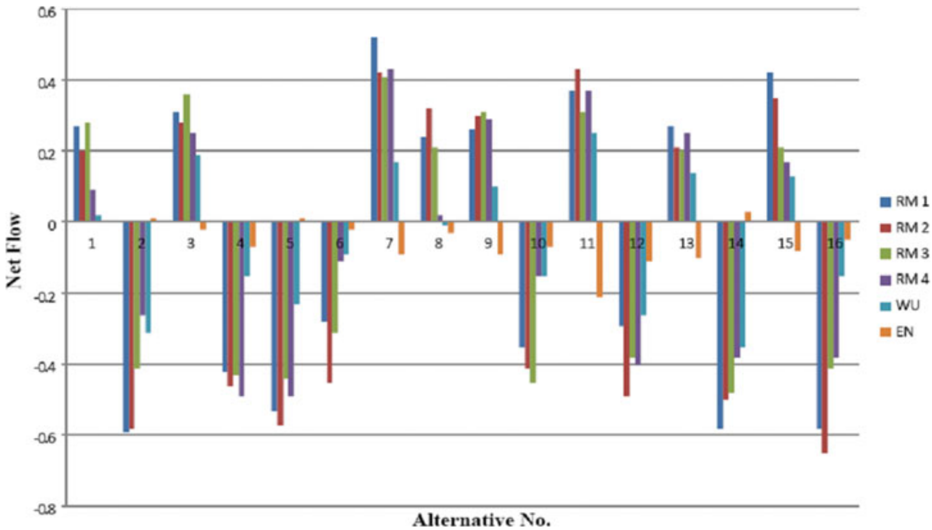

Fig. 5 Net flows of alternatives in scenario No.2

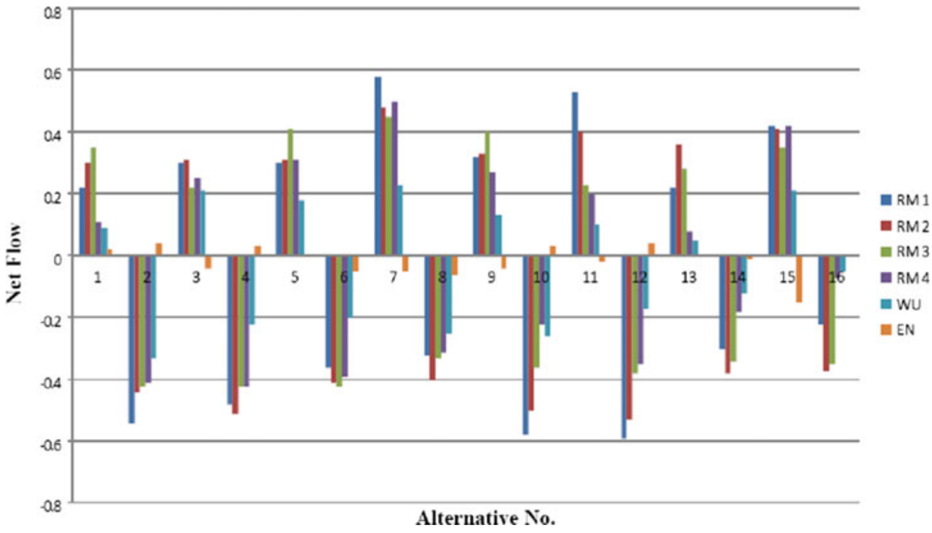

Fig. 6 Net flows of alternatives in scenario No.3

obtained for the three aforementioned scenarios, respectively. It should be noted that the results of the first scenario have been reported by Kodikara (2008). The comparison between the results of these scenarios shows that:

1- The alternative No. 7 is ranked first between the sixteen alternatives in all of the scenarios. This alternative is defined for improving the water supply system of Melbourne in the future. This result shows the robustness of alternative 7 in the ranking process with considering all of the associated criteria.

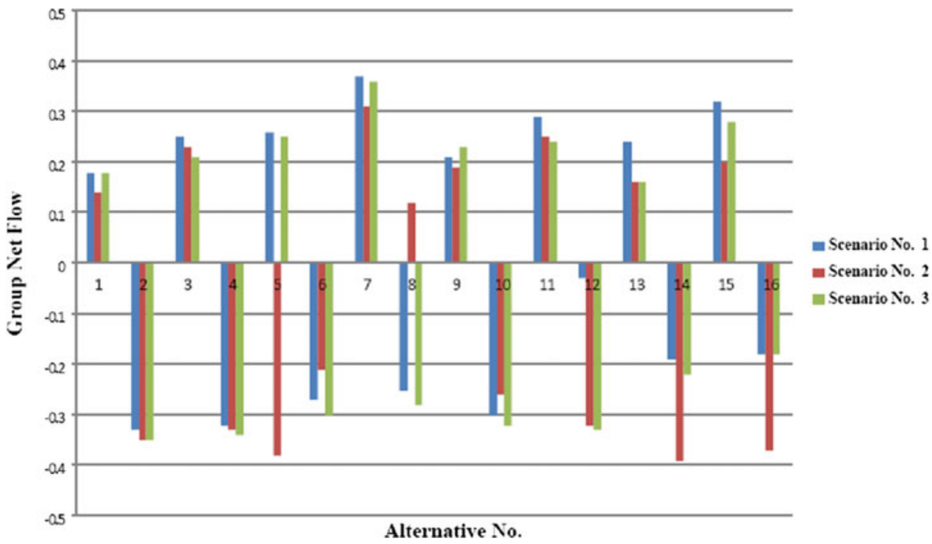

Fig. 7 Net flows for group decision

Table 6 Complete ranking for group decision

Alternative	Scenario No. 1	Scenario No. 2	Scenario No. 3
1	8	7	7
2	16	13	16
3	5	3	6
4	15	12	15
5	4	15	3
6	12	9	12
7	1	1	1
8	11	8	11
9	7	5	5
10	14	10	13
11	3	2	4
12	13	11	14
13	6	6	8
14	10	16	10
15	2	4	2
16	9	14	9

2- Ranking results for the scenarios No. 1 and 3 are almost similar due to the information added to the precedence orders based on the fixed values of weights. It means that if stakeholders are insure about the criteria weights in Table 3, the presented method with c-vectors can have the results near to the decision making with fixed weights.

As it was explained before, to estimate the satisfaction of stakeholders with final group decision making ranking, PSI and GSI indices can be applied for mapping the correlation between DMs' individual ranking and group decision making rankings calculated by the PROMETHEE-GDSS method in this paper. These indices for the three scenarios have been demonstrated in Table 7. The results in this table show that the GSI value for the scenarios No. 2 and 3 have been improved about 20 % and 8 % in comparison with the scenario No. 1 (PROMETHEE with fixed values of criteria weights), respectively. It indicates when uncertainties in allocation of weights to the criteria are high and stakeholders are only sure about their precedence orders, the probability of DMs' satisfaction about the group decision ranking is increased. But the status in which DMs intuitively assign the crisp values to the criteria, leads to the reduction of GSI.

4 Conclusions

In this paper, a new group decision making aid tool, namely PPOC, was presented to help the stakeholders in urban water supply systems in decision problems with different management alternatives and different goals. To examine the capabilities of this method, a case study of Melbourne Water Supply System (Kodikara 2008) was applied to assess sixteen

Table 7 Group Satisfaction Index (GSI)

Scenario No.1	Scenario No.2	Scenario No.3
0.704	0.846	0.761

alternatives with respect to the eight criteria to select the alternative as the best operation policy for water shortage risk reduction in the future and the results of this new model were compared with the conditions where the criteria weights have fixed values for both individual and group decision making states. The results of the case study have shown that the proposed methodology is a systemic way to deal with the complex problem of priority setting. The methodology has a theoretical logic. It is transparent and as a result, the decision makers can understand its technique, participate and understand the meaning of the results so there is a high possibility that they accept them. Using the proposed method has shown the following most important advantages:

1- Decision makers should not assign fixed values of weights to the criteria for indicating the importance of them and they can assign only precedence order to them to find the ranking. When they are not satisfied by the results or the complete ranking is not obtained, decision makers can use additional information on the relative importance of the criteria. It can increase the flexibility of the weights of objectives. So, decision makers can easily evaluate the robustness of the ranking results under different sets of precedence orders and additional information.
2- Uncertainties in the decision matrix and information elicited form decision makers have been incorporated in the decision making process by taking into account the indifference and preference thresholds as well as precedence order determination of weight for each criterion, determined by the decision-makers. The amount of information requested from the decision makers (weights of criteria and thresholds) has proven to be simple and enough to ensure their cooperation.
3- Comparison between the results of the scenario No. 1 with fixed weights in this research and the scenario No. 3 in the work of Kodikara (2008) are almost similar especially for highest ranked scenarios, while satisfaction degrees of DMs in scenarios No. 2 and No.3 in this paper are better than his results because weighting method in these two scenarios is more tangible than Kodikara's direct weighting approach.
4- This PPOC method increases the satisfaction of DMs about the final group decision making results obtained by the PROMETHEE-GDSS methodology.
5- This method is applicable to a wide range of water resources management problems especially in urban water supply systems because of: (1) diversity and number of stockholders and users with different discretions about criteria and their relative parameters such as thresholds' values, (2) consideration of great uncertainties in importance of the criteria and stakeholders' knowledge to attribute them and (3) because this method is simple, it can be applied by high level decision makers such as water managers and low level decision makers such as water users for prioritization of urban water supply plans.

Future studies can focus on some details which are not covered in this paper such as sensitivity analysis of the ranking results with respect to the PRPMETHEE method parameters and additional information of the criteria and comparison of the PPOC results with those obtained from other MCDM techniques.

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