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Abstract

In multiple criteria decision-making (MCDM), decision makers (DMs) always give preferences in alternatives, criteria or decision matrices. Since the DMs may have different cultural and educational backgrounds or different values systems, they may express their preferences in different ways. This is especially the case in the cyberspace environment (Courtney 2001). In this study, the DMs are asked to express their preferences in criteria using any one of the following preference formats: preference orderings, utility values, multiplicative preference relation, selected subset, fuzzy selected subset, normal preference relation, fuzzy preference relation, linguistic terms, and pairwise comparison. In addition, the unifying methods and aggregating methods are also proposed in the paper. Using multiple preference formats provides not only convenience and accuracy in generating the final outcome, but also results in higher satisfaction levels of the DMs with both the decision-making process and the decision outcome. An experiment was conducted to justify the proposed approach.

Keywords: Multiple criteria decision-making; weights; preference format; multiplicative preference relation; geometric means aggregation

Introduction

Decision-making is a knowledge-intensive activity with knowledge as its raw material, work-in-progress, by-product, and finished good (Courtney 2001). Multiple criteria decision-making (MCDM) refers to making preference decisions (e.g. evaluation, prioritisation, selection) on the available alternatives in terms of multiple, usually conflicting, criteria (Huang and Yoon 1981). It is a problem with extensive theoretical and practical backgrounds (Huang and Yoon 1981). It is found that people has certain tendency in MCDM. For example, a decision matrix is used to assist decision-making. In addition, participation of multiple decision makers (DMs) rather than one DM is desirable in most decision-making processes (Chiclana et al. 1999, Herrera et al. 2001, Hwang and Lin 1987, Lee and Kim 2000, Lee and Kim 2001, Zhou 2000). This is because, in the former condition, bias derived from a single DM can be effectively avoided and DMs' partiality can be minified (Lee and Kim 2000).

The traditional solution methods for MCDM problems are confronted with new challenges in the cyberspace environment. Internet technology is widely adopted to facilitate communications among a wide variety of stakeholders and to assist organizational decision-making (Courtney 2001). Under this environment, multiple DMs, who are sparsely distributed all over the world, can be involved in a decision-making process. More than that, DMs with different cultural and educational background can now express their opinion in different formats. They are given the flexibility to choose their preferred formats to show their preferences in making decision (Chiclana et al. 1999, Herrera et al. 2001, Zhou 2000).

In fact, different formats of preference information are necessary for some MCDM problems, such as student information systems (IS) project assessment (Kwok et al. 2001). Current preference formats are not sufficient to support group decision-making in the Electronic Business environment, especially when the information available is fuzzy or uncertain (Chiclana et al. 1998, Herrera et al. 2001). At least, linguistic terms, together with other preference formats, should be provided to DMs for opinion expression, as proposed in Chiclana et al. (1998) and Herrera et al. (2001).

This study considers the situation where preference information on criteria is given from multiple DMs in different formats. These preferences are then used to determine the weights of the criteria. The situation of making decision after gaining consensus of the group of DMs is not considered in this study. Sometimes the group is too large that it is difficult for the group members to negotiate, lobby or compromise with each other. To express their preferences, the following preference information formats are provided to the DMs: preference orderings, utility value, multiplicative preference relation, selected subset, fuzzy selected subset, normal preference relation, fuzzy preference relation, linguistic terms, and pairwise comparison. The preference formats are unified into multiplicative preference relation respectively. After the preference aggregation and exploitation process, the weights of the criteria can be obtained.

The proposed mechanism allows DMs to express their opinions easily and results in a high satisfaction levels on both the decision-making process and outcome. This proposition is justified through a field experiment where a group of students were asked to decide the weights of the criteria for evaluating their coursework assignments. The result validated the proposition. Furthermore, we believe that the way to obtain the weights of criteria for evaluation obtained can be applied to other similar situations.

This paper begins with a brief literature review on the relevant theories and methods. After that, the approach to unify, aggregate and exploit multiple preference formats is proposed in section three. In section four, the use of multiple preference formats in determining criterion weights is validated by measuring the satisfaction levels of the users with both the decision-making process and the decision outcome by means of experiment. The last section is the summary of this paper.

Literature Review

Chiclana et al. (1998) proposed the use of three formats of preference information on alternatives, known as, preference orderings, utility value and fuzzy preference relation. Preference orderings and utility value formats are unified into fuzzy preference relation respectively. The unified preference information is aggregated into a collective fuzzy preference relation by adopting the ordered weighted average (OWA) operator based on the concept of fuzzy majority. Given the collective fuzzy preference relation, the alternative selection process is conducted by calculating the quantifier guided dominance degree (QGDD) and the quantifier guided non-dominance degree (QGNDD) for each alternative. The QGDD and QGNDD of each alternative are also calculated by using OWA operator based on the concept of fuzzy majority. However, the fuzzy majority guided OWA operator cannot be used to determine the relative importance of the alternatives.

With multiplicative preference relation as the basic preference format, Herrera et al. (2001) used ordered weighted geometric (OWG) operator to aggregate three formats of preference information: preference orderings, utility value and multiplicative preference relation. The former two formats of preference information are unified into the last one respectively. Based on the fuzzy majority concept with fuzzy linguistic quantifier, OWG operator is used to aggregate the unified preference information. Based on the aggregation result and the concept of fuzzy majority, the quantifier guided dominance degree (MQGDD) and the quantifier guided non-dominance degree (MQGNDD) of each alternative are used to select the most desirable alternative(s).

As an extension of the previous approaches, we intend to explore in this study another way to make use of the multiplicative preference relation and other formats of preference information expression. Multiple preference formats are unified and aggregated into multiplicative preference relation. Finally, based on the collective multiplicative preference relation, weighted geometric means aggregation method is used to determine the relative importance of the criteria.

The Proposed Approach

To facilitate describing the proposed approach, the following assumptions and notations are used:

- The alternatives are known. Let $S = \{S_1, S_2, \cdots, S_m\}$ denotes a discrete set of $m\ (\geq 2)$ possible alternatives.
- The criteria are known. Let $C = \{C_1, C_2, \cdots, C_n\}$ denotes a set of $n\ (\geq 2)$ criteria. The criteria are assumed additively independent.

- The vector of criterion weights is unknown. Let $w = (w_1, w_2, \cdots, w_n)^T$ be the vector of criterion weights, where $\sum_{j=1}^{n} w_j = 1$, $w_j \geq 0$, $j = 1, \cdots, n$, and w_j denotes the weight of criterion C_j. Usually *w* should be determined in the course of decision-making.
- The decision makers (DMs) are known. Let $E = \{e_1, e_2, \cdots, e_K\}$ denote the set of *K* ($K \geq 2$) Dms.

Unify Preference Formats into Multiplicative Preference Relation

In this study, the uniform preference format is multiplicative preference relation (Herrera et al. 2001). The ways to transform different preference formats into a single one are shown as follows:

(0) **Multiplicative preference relation** or pairwise comparison. DMs' preferences on criteria can be described by a positive preference relation. The intensity of preference is measured using a ratio scale, such as Saaty's "1 to 9 scale" (Saaty 1980). "1" indicates indifference between two subjects when "9" indicates that one subject is absolutely preferred to the other. The intermediate preferences are expressed in "2", "3",…, "8". The preference relation matrix is assumed multiplicative reciprocal (Saaty 1980).

(1) ***Preference orderings*** or an ordered vector. Let $O^k = (o^k(1), \cdots, o^k(n))$ be an ordered vector used by a DM e_k ($e_k \in E$) to express his preference on criteria (Chiclana et al. 1998, Herrera et al. 2001). $o^k(\cdot)$ is a permutation function over the index set {1, …, *n*} and $o^k(i)$ represents the ranking position of criterion C_i, $i = 1, \cdots, n$. The criteria are ranked from the best to the worst.

Herrera et al. (2001) discussed the methods for transforming an ordered vector into multiplicative preference relation. Commonly, the preference orderings O^k can be transformed into multiplicative preference relation on the criteria C_i and C_j as follows (Herrera et al. 2001):

$$p_{ij}^k = 9^{u_i^k - u_j^k} \qquad i, j = 1, \cdots, n, \tag{1}$$

In this equation, $u_i^k = v(n - o^k(i))$ and $u_j^k = v(n - o^k(j))$ are utility values associated with criteria C_i and C_j respectively, obtained by considering the effect of an increasing function *v*, such as $u_i^k = (n - o^k(i))/(n-1)$

(2) ***Utility value*** or a utility vector. Let $U^k = (u_1^k, u_2^k, \cdots, u_n^k)$ be a utility vector provided by a DM e_k, $e_k \in E$, where $u_i^k \in [0,1]$, $i = 1, \cdots, n$ and u_i^k represents the utility value given by e_k to criterion C_i.

Again, Herrera et al. (2001) discussed the methods for transforming a utility vector into multiplicative preference relation. The utility vector $U^k = (u_1^k, u_2^k, \cdots, u_n^k)$ can be transformed into multiplicative preference relation on criteria C_i and C_j as follows (Herrera et al., 2001):

$$p_{ij}^k = \frac{u_i^k}{u_j^k}, \qquad i, j = 1, \cdots, n. \tag{2}$$

(3) ***A vector of linguistic terms on C.*** Let $L^k = (l_1^k, l_2^k, \cdots, l_n^k)$ be a linguistic term vector given by a DM e_k, $e_k \in E$. The notion l_i^k represents the linguistic evaluation given by e_k to criterion C_i, $i = 1, \cdots, n$, $e_k \in E$.

Suppose two criteria C_i and C_j are awarded linguistic terms $l_i^k = (u_i, \alpha_i, \beta_i)$ and $l_j^k = (u_j, \alpha_j, \beta_j)$ respectively. For simplicity, the following function is used in this study to transform $l_i^k = (u_i, \alpha_i, \beta_i)$ and $l_j^k = (u_j, \alpha_j, \beta_j)$ into multiplicative preference relation on criteria C_i and C_j:

$$p_{ij}^k = 9^{u_i - u_j}. \qquad i, j = 1, \cdots, n. \tag{3}$$

(4) ***A selected subset of C.*** Let $\overline{C} = \{C_{i\_1}, C_{i\_2}, \cdots, C_{i\_t}\}$ be a selected subset of *C* used by a DM e_k, $e_k \in E$, to express his preference on part of the criteria. $\overline{C} \subset C$, $i\_t < n$. Criteria in $\overline{C}$ are equivalent to each other and dominate those on the left of *C*. The criteria in $C / \overline{C}$ are also equivalent to each other.

Given the selected subset of *C*, $\overline{C} = \{C_{i\_1}, C_{i\_2}, \cdots, C_{i\_t}\}$, the multiplicative preference relation on any two criteria C_i and C_j in *C* can be defined as,

$$p_{ij}^k = 9 \text{ and } p_{ji}^k = 1/9, \quad i, j = 1, \cdots, n; i \neq j, \quad if\ C_i \in \overline{C},\ C_j \in C/\overline{C} \tag{4}$$

$$p_{ij}^k = p_{ji}^k = 1, \qquad i, j = 1, \cdots, n, \qquad \text{otherwise.} \tag{5}$$

(5) ***A fuzzy selected subset of C.*** Let $\widetilde{C} = \{(C_{i\_1}, l_{i\_1}^k), (C_{i\_2}, l_{i\_2}^k), \cdots, (C_{i\_q}, l_{i\_q}^k)\}$, $i\_q < n$, be a fuzzy selected subset of *C* used by a DM e_k, $e_k \in E$, to express his preference on part of the criteria using linguistic terms. $l_{i\_r}^k$ is a linguistic term in this paper, $i\_r = 1, \cdots, i\_q$.

For example, a DM thinks that criterion C_i is "good", C_j is "very good", and criteria C_h and C_l are both "fair". For any two criteria C_i and C_j in *C*, if they both belong to $\widetilde{C}$, where $l_i^k = (u_i, \alpha_i, \beta_i)$ and $l_j^k = (u_j, \alpha_j, \beta_j)$, then the multiplicative preference relation on them can be defined as:

$$p_{ij}^k = 9^{u_i - u_j}. \qquad i, j = 1, \cdots, n; i \neq j. \tag{6}$$

If none of the two criteria C_i and C_j belong to $\widetilde{C}$, then

$$p_{ij}^k = 1, \qquad i, j = 1, \cdots, n; i \neq j. \tag{7}$$

If criterion C_i belongs to $\widetilde{C}$ and C_j does not belong to $\widetilde{C}$, then

$$p_{ij}^k = 9^{u_i - 0.5}, \qquad i, j = 1, \cdots, n; i \neq j. \tag{9}$$

(6) ***Normal preference relation.*** Normal preference relation on criteria can be given by a DM to express his/her strict preferences to the criteria. For example, DM e_k, prefers criterion C_i to C_j, and prefers criterion C_c to criteria C_l and C_h.

In this case, for the criteria with strict preference relationships, their multiplicative preference relations are 9 ver $1/9$. Thus, $p_{ij}^k = 9$ and $p_{ji}^k = 1/9$; $p_{cl}^k = 9$ and $p_{lc}^k = 1/9$; $p_{ic}^k = 1$ and $p_{lh}^k = 1$.

(7) ***Fuzzy preference relation.*** The DMs' preference relation is described by a binary fuzzy relation *F* in *C*, where *F* is a mapping $C \times C \rightarrow [0, 1]$ and f_{ij} denotes the preference degree of criterion C_i over C_j. *F* is assumed to be reciprocal. By definition (Chiclana et al. 1998, Kacprzyk et al. 1992), (i) $f_{ij} + f_{ji} = 1$, $i, j = 1, \cdots, n; i \neq j$, and (ii) $f_{ii} = -$ (symbol '–' means that the DM does not need to give any preference information on criterion C_i), $\forall i$.

Fuzzy preference relation can be transformed into multiplicative preference relation as follows:

$$p_{ij}^k = \frac{f_{ij}^k}{f_{ji}^k}, \qquad i, j = 1, \cdots, n. \tag{9}$$

Aggregating the Multiplicative Preference Relations from Multiple DMs

After unifying the multiple preference formats to one single format, the next step is aggregating and exploiting multiplicative preference relations from multiple DMs. The methods proposed are described in detail below.

Fuzzy Majority Method (Herrera et al. 2001)

Denote $P^l = (p_{ij}^l)_{n \times n}$ as the individual multiplicative preference relation on criteria from DM e_l, *l* =1,···, *K*. A collective multiplicative preference relation $P^C = (p_{ij}^c)_{n \times n}$ can be obtained according to the opinions of majority of the DMs'. Traditionally, the majority is defined as a threshold number of individuals. Fuzzy majority is a soft majority concept expressed by a fuzzy linguistic quantifier (Zadeh 1975, 1983). p_{ij}^c can be calculated by using the ordered weighted aggregation (OWG) operator, defined as follows.

Let $p_{ij}^1, p_{ij}^2, \cdots, p_{ij}^K$ be a list of values to be aggregated. The OWG operator of dimension *K* is a function ϕ^G,

$$\phi^G : R^K \rightarrow R$$

which is associated with a set of weights λ. λ is defined as

$$\phi^G(p_{ij}^1, p_{ij}^2, \cdots, p_{ij}^K) = \prod_{l=1}^{K} (z_l)^{\lambda_l}, \tag{10}$$

where $\lambda = [\lambda_1, \cdots, \lambda_K]$ is an exponential weighting vector such that $\lambda_l \in [0,1]$, *l*=1,···, *K*, and $\sum_{l=1}^{K} \lambda_l = 1$. *Z* is the associated ordered value vector. Each element $z_l \in Z$ is the l^{th} largest value in the collection { $p_{ij}^1, p_{ij}^2, \cdots, p_{ij}^K$ }. The concept of fuzzy majority is used to calculate the weighting vector λ by means of a fuzzy linguistic quantifier according to Yager's ideas (1993, 1996). In the case of a non-decreasing proportional quantifier *Q*, the weighting vector λ is calculated using the following expression (Yager, 1993, 1996):

$$\lambda_l = Q(l / K) - Q((l-1)/K), \qquad l = 1, \cdots, K. \tag{11}$$

When a fuzzy linguistic quantifier *Q* is used to calculate the weight vector λ in the OWG operator ϕ^G, it is represented by ϕ_Q^G. Therefore, the collective multiplicative preference relation is obtained as follows:

$$p_{ij}^{c} = \phi_{Q}^{G}(p_{ij}^{1}, p_{ij}^{2}, \cdots, p_{ij}^{K}), \qquad i, j = 1, \cdots, n; i \neq j . \tag{12}$$

Geometric Means Aggregation Rule for Aggregation Across Multiple DMs

Again, denote $P^{l} = (p_{ij}^{l})_{n \times n}$ as the individual multiplicative preference relation on the criteria from DM e_l, l =1,···, K. A collective multiplicative preference relation $P^{C} = (p_{ij}^{c})_{n \times n}$ can be obtained by using the geometric means aggregation rule (Barzilai and Lootsma 1997):

$$p_{ij}^{c} = \prod_{l=1}^{K} (p_{ij}^{l})^{T_l}, \qquad i, j = 1, \cdots, n; i \neq j . \tag{13}$$

where T_l is the power coefficient of DM e_l, l =1,···, K. In this study, DMs are treated equally unless specification.

Geometric Means Aggregation Rule for Exploitation

Given the collective multiplicative preference relation $P^{C} = (p_{ij}^{c})_{n \times n}$, the geometric means aggregation rule can be used again to obtain the overall values of the criteria,

$$d_i = [\prod_{j=1}^{n} \prod_{l=1}^{K} (p_{ij}^{l})^{1/K}]^{1/n}, \qquad i = 1, \cdots, n . \tag{14}$$

Normalize d_i, $i = 1, \cdots, n$, the weight vector w of the criteria can then be obtained.

Validation of the Use of Multiple Preference Formats

In solving the student Information Systems (IS) project assessment problem, Kwok et al. (2001) proposed the use of different formats in presenting individual preferences. Since the assessment criteria are different in nature, it is necessary to use different preference formats to assess the IS projects against different criteria (a MCDM problem). A similar scenario in the form of laboratory experiment is adopted in this study to validate the following hypothesis:

> **Hypothesis.** The use of multiple preference formats in decision-making results in higher satisfaction levels with both the decision-making process and the decision outcome than those from single preference format.

Experiment Design

Subjects: The subjects are one hundred second year undergraduate business students who attended a course called "Data Management" in Fall 2001. They had to build a database in order to fulfill the coursework requirement. 58% of them are male and 42% are female. The average age is 20.3 years old. Eventually, the effective sample size is sixty-four where thirty-one students in the experimental group and thirty-three in the control group.

Task: At the beginning of the experiment, the facilitator announced that the task of the experiment was to collect students' opinions on the marking scheme in evaluating their coursework. Students were asked to express their opinions on the weights (or relative importance) of the four criteria: C_1 "ease of use", C_2 "security", C_3 "reliability" and C_4 "response time". The facilitator then introduced the format(s) to be used by the students. Students had to make their own decision without negotiating or compromising with each other. In order to do so, students are not allowed to communicate with others throughout the experiment. During the experiment, students in the control group could express their opinions on the weights of the criteria by using only one format, i.e., utility value or an utility vector (u_1, ..., u_4). u_i ($0< u_i <=1$, i=1,2,3,4) represents the utility evaluation given to the ith criterion. Students in the experimental group could use any one of the eight preference formats discussed above. After that, the facilitator ran a program to calculate the weights of the criteria based on the students' opinions. Lastly, students were asked to complete a questionnaire measuring their satisfaction levels with both the decision-making process and the decision outcome, as shown in Appendix A.

Measurement of the Satisfaction of Students

Two dependent variables were measured: the satisfaction levels of students with the evaluation process and with the evaluation outcome. To capture the satisfaction levels, a questionnaire with six questions was provided to the students after criteria evaluation (see Appendix A for details).

Tests on the Instrument

Table 1 shows that the correlation coefficients between the scores on the first four questions and on the fifth question (overall satisfaction level with decision-making process) are . In addition, the correlation coefficients between the average scores across question 1 to question 4 and that of question 5 justify the use of the four questions in measuring students' satisfaction levels on the decision-making process. The use of these questions for measuring satisfaction on decision-making process is valid.

Table 1. Correlation Coefficients Among the Questions and the Average score of Questions 1 to 4

	Q1	Q2	Q3	Q4	Q5
Q1	-	-	-	-	-
Q2	0.6559	-	-	-	-
Q3	0.5871	0.6621	-	-	-
Q4	0.4880	0.6542	0.5675	-	-
Q5	0.6429	0.7902	0.6470	0.5790	-
Average (Q1 to Q4)	0.8225	0.8882	0.8391	0.8008	0.7948

Except the inter-item correlation, reliability score of the instrument is also computed. The figure 0.8933 suggests it is an instrument with high reliability. The questions can reflect accurately capture the satisfaction level of the subjects with the decision-making process.

Findings and Discussion

The preference exploitation process is proposed to determine the weights of evaluation criteria based on DMs' preferences. With these methods, preferences expressed in different formats mentioned above can be transformed to a single one. This provides convenience and accuracy in generating a final outcome based on the opinions of multiple Dms.

In addition to the advantages discussed above, the use of multiple preferences formats also results in higher satisfaction levels of the DMs with both the decision-making process and the decision outcome. To compare the means of the students' satisfaction levels with both the decision-making process and the decision outcome between the control group and the experimental group, independent t-test was employed. The results are listed in Table 2 and 3 respectively (Clover and Balsley 1984, Cooper and Schindler 2001, Zikmund 1997).

In Table 2, the results for Levene's Test for Equality of Variances are: F-value is 1.573 and the significance coefficient is 0.215. These results justify that the variances of the students' satisfaction levels with the decision-making process can be thought as the same, which supports the use of the t-test. The p value in suggests that there is a significant difference in the satisfaction level with the decision-making process between the students in control group and those in experimental group. It implies that the students using multiple preference formats have higher satisfaction with the decision-making process than those using single format.

Table 2. Effect of Using Multiple Preference Formats on Students' Satisfaction Levels with Evaluation Process

Measure	Mean (Standard deviation) for using **single** preference format	Mean (Standard deviation) for using **multiple** preference formats	t_value (two tailed)	p_value	Levene's Test	
					F-value	Sig.
Satisfaction Level	2.42 (0.66)	3.74 (0.68)	7.84	0.000	1.573	0.215

Table 3. Effect of Using Multiple Preference Formats on Students' Satisfaction Level with Evaluation Outcome

Measure	Mean (Standard deviation) for using **single** preference format	Mean (Standard deviation) for using **multiple** preference formats	t_value (two tailed)	p_value	Levene's Test	
					F-value	Sig.
Satisfaction Level	2.52 (0.71)	3.71 (0.64)	7.028	0.000	0.769	0.384

Similarly in Table 3, the results for Levene's Test for Equality of Variances are: F value is 0.769 and the significance coefficient is 0.384. These results justify that the variances of the students' satisfaction level with the decision outcome can be thought as the same, which supports the use of the t-test. Once again, the low p value implies a significant difference in the satisfaction level with the decision outcome between the students in control group and those in experimental group. In other words, the students using multiple preference formats have higher satisfaction with the decision outcome than those using single format.

Conclusion

In this study, the problem of providing preference information on criteria is investigated. Multiple DMs tend to express their preferences on the criteria in different formats due to their different cultural and educational backgrounds, and their different value systems. This is obvious the case in the cyberspace environment. This paper proposes an approach to provide more flexibility to DMs in expressing their opinions by extending the number of preference formats from single to multiple. The unifying methods and aggregating methods are also discussed in the paper. The preference exploitation process is used to determine the weights of the criteria. The experiment justifies the proposed approach in using multiple preference formats. Using the proposed formats to express preference information would provide more flexibility in MCDM and would result in higher satisfaction level on both the decision-making process and the decision outcome. On top of that, this mechanism can be applied on other similar decision-making situations, which will be an ideal research focus.

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Appendix A
Questions Used to Measure Students' Satisfaction Levels

Question 1: It is easy for me to express my opinions by using the provided preference format(s).
Question 2: I can sufficiently express my opinions.
Question 3: I can precisely express my opinions.
Question 4: The preference format(s) provided is suitable for me.
Question 5: I am satisfied with the process of expressing my opinions.
Question 6: I am satisfied with the evaluation outcome by expressing my opinions.

The answers are on a Likert scale from 1 to 5, corresponding to strongly disagree, disagree, fair, agree and strongly agree. When they have finished evaluating a criterion, students are given these questions to measure their satisfaction levels with the evaluation process and with the evaluation outcome.