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Application of Multiattribute Decision-Making Methods for the Determination of Relative Significance Factor of Impact Categories

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ABSTRACT / A relative significance factor (f_i) of an impact category is the external weight of the impact category. The objective of this study is to propose a systematic and easy-to-use method for the determination of f_i. Multiattribute decision-making (MADM) methods including the analytical hierarchy process (AHP), the rank-order centroid method, and the fuzzy method were evaluated for this purpose. The results and practical aspects of using the three methods are compared. Each method shows the same trend, with minor differences in the value of f_i. Thus, all three methods can be applied to the determination of f_i. The rank order centroid method reduces the number of pairwise comparisons by placing the alternatives in order, although it has inherent weakness over the fuzzy method in expressing the degree of vagueness associated with assigning weights to criteria and alternatives. The rank order centroid method is considered a practical method for the determination of f_i because it is easier and simpler to use compared to the AHP and the fuzzy method.

Over the last decade interest in environmental issues has grown significantly. Ever-increasing attention has been paid to the environmental impacts from the manufacture, use, and disposal of various products. Life cycle assessment (LCA) has been widely used in evaluating the environmental aspects of a product system. LCA is a systematic tool to evaluate the environmental aspects and potential impacts throughout a product's life (i.e., from cradle to grave) from raw material acquisition, through production, use, transportation and disposal (ISO 1997).

One of the major applications of LCA is to provide information about environmental aspects of a product system to the decision-makers of an organization. Thus, decision makers can take into account not only economical and technical aspects but also environmental aspects in their decision-making. The application of the LCA results into the product development process will be expedited if the results are expressed as a single score. Single-index results are also easier to communicate to the public. Therefore, a weighting step should be carried out in the life cycle impact assessment (LCIA) phase. According to ISO 14042 (ISO 2000), weighting is defined as a process of converting indicator results of different impact categories by using numerical factors based on value choices, and this step is treated as an optional element.

In general, weighting methods can be classified into qualitative (including semiquantitative) and quantitative methods (Finnveden 1996). There are three common approaches to select weighting factors in the quantitative methods. They are expert panel methods, monetization methods, and distance-to-target methods (Finnveden 1996, Lindeijer 1996). In the expert panel methods, a group of experts are requested to assign numerical value to impact categories based on the degree of significance of an impact category with respect to other impact categories. The resulting weight represents the relative significance of an impact category. Thus, the weight can be termed as a relative significance factor. The arbitrary nature of the panel methods, however, is a weakness.

Monetization methods are based on "willingness to pay," which is determined by assessing the negative value of the damage or impact. The willingness to pay is normally related to the avoidance of something; thus, somebody is willing to pay a certain amount of money in order to avoid something. The methods are a combination of damage to the safeguard area and money to fix the damage.

Distance-to-target methods are well established and widely used in LCIA. In the distance-to-target methods, weights are derived from the extent to which actual environmental performance deviates from some goal and standard. The methods rank impacts as being more

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important the further away society's activities are from achieving the desired targets for the pollutants. However, distance-to-target methods have several specific problems (Lindfors and Others 1995, Finnveden 1996, Lee 1999, Seppälä and Hämäläinen 2001). As described by these mentioned authors, the distance-to-target methods are not weighting methods at all. They can be considered another form of normalization.

Lee (1999) proposed a new weighting approach that combined the distance-to-target method and the expert panel method. The reduction factor (*RF*) in the distance-to-target method and the relative significance factor (f_i) in the expert panel method are multiplied to generate a new weighting factor. The *RF* reflects the internal aspect of an impact category and indicates the degree of seriousness of today's impact in relation to that of tomorrow's impact. In contrast to this, the f_i reflects the external aspect of an impact category and indicates the significance of the impact category with respect to the other impact categories.

Determination of the relative significance factor of the impact categories can be modeled with the multiattribute decision-making (MADM) methods because they can provide a useful framework for determining the weighting factor (Seppälä and others 2002). Therefore the objective of this study is to evaluate existing MADM methods and propose an easy-to-use MADM method for the determination of f_i.

Methodology Overview

Relative Significance Factor

The value of f_i can be used as a weight in the expert panel methods or as one of two factors needed for the calculation of weight consisting of *RF* and f_i proposed by Lee (1999). When there are n numbers of impact categories, the sum of f_i is expressed as equation 1.

$$\sum_{i}^{n} f_i = 1 \qquad (1)$$

The f_i can be expressed as a product between weight of the criteria and weight of the alternative on the criteria. Equation 2 shows this relationship, where C_k is a weight of the kth criteria, and $Z_{i,k}$ is a weight of the ith alternative on the kth criteria.

$$f_i = \sum_{k} C_k Z_{i,k} \qquad (2)$$

MADM Methods

In many decision-making situations it is desirable to achieve or respond to several objectives at once. Because different alternatives have different levels of performance with respect to different objectives, it is rare to find a single alternative that performs best with respect to all the objectives at once. For this reason, a number of different methods have been developed to help decision-makers identify and select preferred alternatives. These so-called MADM methods are a group of decision analysis methods where there are several criteria affecting the selection of a desirable alternative related to one goal. The AHP, the rank-order centroid method, and the fuzzy method were chosen in this study. In this section we briefly describe the basic concepts of each method.

AHP

The AHP (Saaty 1980) has been widely used for MADM specifically designed for decisions that require integration of quantitative data with less tangible, qualitative considerations such as values and preferences, especially in situations where there are important qualitative aspects that require consideration in conjunction with various measurable quantitative factors. The AHP is based on three steps. The first step is to structure the decision problem in a hierarchy. The second step is the comparison of the alternatives and the criteria. The last step is to synthesize the comparisons to get the weights of alternatives with respect to each criterion and the weights of each criterion with respect to the goal. A rating scale of 1 to 9 is generally used to reflect the relative preference of one factor over another in pairwise comparison.

Rank-Order Method

Experts can rank the order of significance of the criteria and alternatives based on their own judgments. There are several methods of generating weights from the rank-order information obtained. They include rank-order centroid, rank reciprocal, and rank sum (Stillwell and Others 1981). The rank-order centroid method is the most widely used method (Barron and Barrett 1996) and was adopted as the rank-order method of choice in this study. Weights in this method are expressed in equation 3, where i is the ith rank order, and n is the number of alternatives.

$$w_i = \frac{1}{n} \sum_{k=i}^{n} \frac{1}{k} \qquad i = 1,2, \ldots, n. \qquad (3)$$

The rank order centroid method, in general, is difficult to apply when the number of alternatives exceeds ten. The optimum number of alternatives ranges from five to nine.

Fuzzy Method

The fuzzy logic developed by Zadeh (1965) provides a remarkably simple way to draw definite conclusions from vague, ambiguous, or imprecise information. Fuzzy logic allows expressing knowledge with subjective concepts such as very hot, bright red, and a beautiful girl that are mapped into exact numeric ranges. This method uses everyday words for rating and translates these linguistic variables into fuzzy sets for subsequent operations (Ghotb and Warren 1995). The concept of linguistic variable is very useful in dealing with situations that are too complex or too ill-defined to be reasonably described in conventional quantitative expressions. A linguistic variable is a variable whose values are words or sentences in natural or artificial language. For example, weight is a linguistic variable, its values are very low, low, medium, high, very high, etc. (Liang and Wang 1991).

Triangular fuzzy number. The membership function of a triangular fuzzy number, $\tilde{A}$, is defined in general form as equation 4, where $\mu_{\tilde{A}}(x)$ is the degree of membership or membership function value of x in $\tilde{A}$; and a, b, and c are real numbers. The triangular fuzzy number, as given by equation 4, can be denoted by a triplet (a, b, c).

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x < a, \\ \dfrac{x-a}{b-a}, & a \leq x \leq b, \\ \dfrac{c-x}{c-b}, & b \leq x \leq c, \\ 0, & x > c \end{cases} . \tag{4}$$

Aggregating and ranking of fuzzy numbers. Let W_t be the importance weight of the decision criterion C_b, let S_{it} be the fuzzy rating for the degree of appropriateness of the decision alternative A_i under C_b, and let F_i be the fuzzy appropriateness index of the A_i. F_i represents the degree of appropriateness of the decision alternative under the decision criteria, and is obtained by aggregating S_{it} and W_t (Chang and Chen 1994). Substituting S_{it} and W_t for triangular fuzzy numbers, that is, $S_{it} = (o_{it}, p_{it}, q_{it})$ and $W_t = (a_t, b_t, c_t)$, F_i can be approximated as in equation 5, where $Y_i = (1/k)\sum_t o_{it} \cdot a_t$, $Q_j = (1/k)\sum_t p_{it} \cdot b_t$, and $Z_i = (1/k)\sum_t q_{it} \cdot c_t$ for $i = 1, 2, \ldots, n$ and $t = 1, 2, \ldots, k$.

$$F_i \cong (Y_i,\ Q_j,\ Z_i) \tag{5}$$

Decision-makers can evaluate alternatives using fuzzy numbers. This can be done by ranking fuzzy numbers and then selecting the highest fuzzy number as the best alternative. Since the aggregated assessments are represented as triangular fuzzy numbers, a method to rank the triangular fuzzy numbers is required. There are several methods for ranking the fuzzy numbers; in this study, the total integral value method is used because of the ease of use (Liou and Wang 1992). Let the total integral value for triangular fuzzy number, $A = (a, b, c)$, be defined as in equation 6. Here, α indicates an index of optimism that represents the tendency of the experts rendering judgment and $0 \leq \alpha \leq 1$.

$$1^{\alpha}_{T}(A) = \frac{1}{2}\left[ac + b + (1 - \alpha)a\right] \tag{6}$$

Application of MADM Methods

Representation of the Decision Problem

In this study the goal of the decision-making is to determine the relative significance of impact categories. This is a slight modification from the typical goal setting in the MADM method, i.e., selection of the best alternative. Instead, assigning weight to the alternatives or relative significance of the impact categories is the goal in this study.

Time, area, irreversibility, and scientific uncertainty were chosen as criteria. These four criteria are considered in the precautionary principle commonly used in life cycle impact assessment (Udo de Haes 1996). The time criterion suggests that environmental problems over an extended period are more serious than those over a shorter period. For the area, environmental problems affecting a wider area are more serious than affecting a smaller area. Irreversible environmental problems are more identified are more serious than those clearly identified.

Impact categories are alternatives. A total of eight impact categories were considered in this study. They are abiotic resources depletion (ARD), global warming (GW), ozone layer depletion (OD), eutrophication (Eutro), acidification (Acid), photochemical oxidant creation (POC), ecotoxicity (ET) and human toxicity (HT). These impact categories were considered in the Korean ecoindicator method (Lee 1999).

A hierarchy consisting of goal, criteria and alternatives depicted in Figure 1 has been established for the determination of f_i based on MADM methods. The hierarchy structure is applied to all three methods described here.

AHP

Figure 2 shows the procedure for calculating the weights of the criteria and the alternatives on the criteria. Here, all weights are obtained from the pairwise comparison between criteria and between alternatives

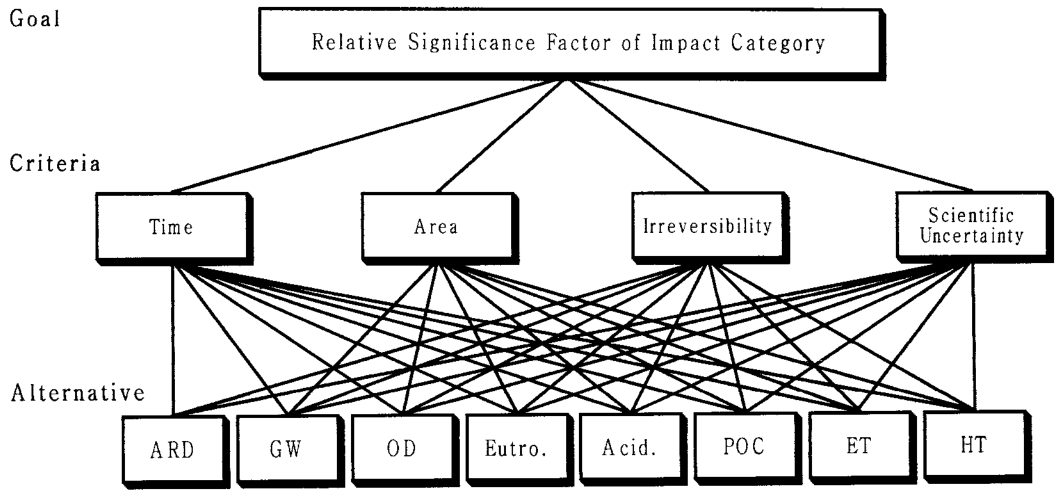

Figure 1. Structure of the hierarchy for the determination of f_i.

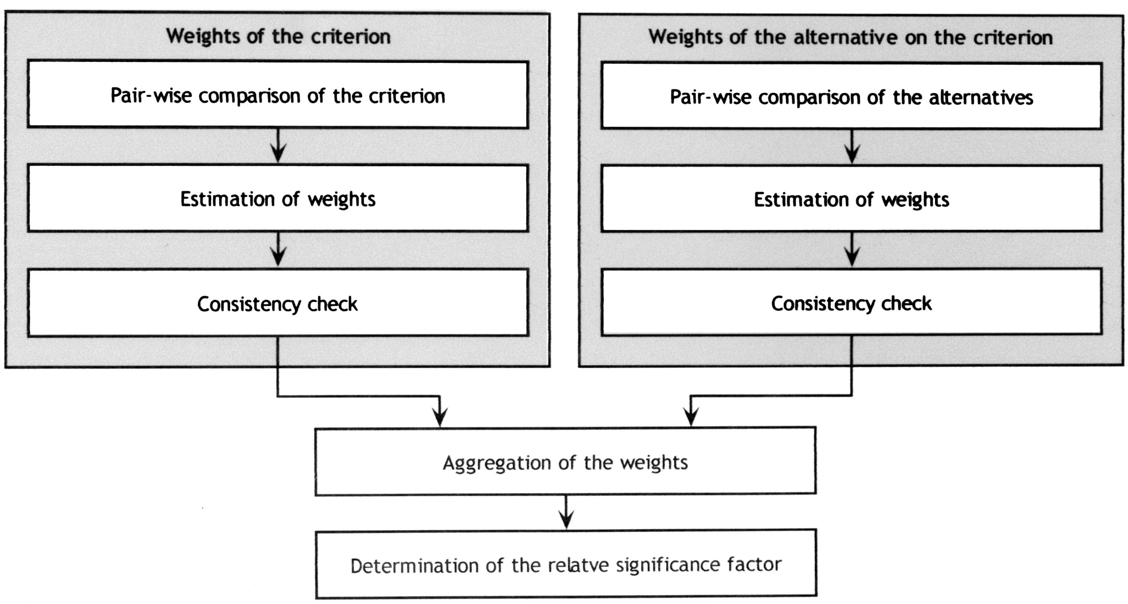

Figure 2. Steps for the determination of f_i based on the AHP.

on the criteria by experts. Combining two types of weight results in f_i.

Pairwise comparison. Table 1 shows the result of pairwise comparison of the four criteria by Korean LCA experts. Although there are several techniques to calculate weight, the results from different techniques are very similar. In this study, weight was calculated with a geometric mean because it is easy to calculate. As shown in Table 1 the weight of time (0.439) was the largest, followed by area (0.311), irreversibility (0.146), and scientific uncertainty (0.104). Based on pairwise comparison by the same group of experts, the weights of alternatives on each criterion were calculated.

Determination of relative significance factor. Table 2 shows the values of f_i based on the AHP. The f_i for ARD, for example, was determined as: 0.250 [= (0.439 × 0.290) + (0.311 × 0.220) + (0.146 × 0.287) + (0.104 × 0.120)]. As shown in Table 2, abiotic resource depletion and global warming are the two most significant impact categories, followed by ozone layer depletion, human toxicity, and ecotoxicity. Acidification and photochemical oxidant creation were considered low

Table 1. Pairwise comparison matrix of the four criteria

Criteria	Time	Area	Irreversibility	Uncertainty	Weight
Time	1	2	3	3	0.439
Area	1/2	1	3	3	0.311
Irreversibility	1/3	1/3	1	2	0.146
Uncertainty	1/3	1/3	1/2	1	0.104

Table 2. Relative significance factor of impact categories based on AHP

	Time (0.439)	Area (0.311)	Irreversibility (0.146)	Uncertainty (0.104)	f_i
ARD	0.290	0.220	0.287	0.120	0.250
GW	0.223	0.286	0.221	0.282	0.248
OD	0.171	0.169	0.169	0.079	0.161
Eutro	0.036	0.035	0.036	0.026	0.035
Acid	0.058	0.058	0.058	0.055	0.058
POC	0.022	0.021	0.021	0.043	0.024
ET	0.088	0.124	0.097	0.169	0.108
HT	0.110	0.087	0.117	0.226	0.116

in significance. The reason for the higher f_i for abiotic resources depletion was because of the higher weight achieved in the two most significant criteria, time and area. In the case of global warming, weights were high in all four criteria.

Rank-Order Centroid Method

The number of pairwise comparisons in the AHP continues to grow as the number of alternatives grows. If there are n alternatives, the number of pairwise comparisons is ${}_NC_2$. When there are m criteria, the total number of pairwise comparisons becomes $m \times {}_NC_2$. This indicates that the increase in the number of alternatives algebraically will increase the number of pairwise comparisons geometrically. The increase in the number of pairwise comparisons suggests increasing difficulties for experts rendering consistent judgment on pairwise comparison (Golden and others 1989). Pairwise comparisons are sometimes difficult and tedious, and the 9-grade linear rating scale (numeric or linguistic) does not always translate well marginal difference of importance. (Ghotb and Warren 1995). Several other rating scales have been proposed that may solve this problem.

The rank-order centroid method can assist in reducing the number of pairwise comparisons by placing the alternatives in order. In this study we proposed to apply the rank order centroid method for the determination of f_i. In this method, weights of criteria are determined, just like in the AHP, through pair-wise comparison between criteria, while weights of the alternatives are determined using the RCOM based on the order information of the alternatives. The benefit of using the rank order centroid method would be the reduction of the number of pairwise comparisons.

Table 3. Ranking of impact categories

	Time	Area	Irreversibility	Uncertainty
ARD	1	2	1	4
GW	2	1	2	1
OD	3	3	3	5
Eutro	7	7	7	8
Acid	6	6	6	6
POC	8	8	8	7
ET	5	4	5	3
HT	4	5	4	2

Ranking of the order. Table 3 shows the rank-order information of the alternatives (impact categories) judged by a group of Korean LCA experts. The same criteria used for AHP were applied in rendering judgment.

Determination of the relative significance factor. Table 4 shows the values of f_i based on the rank-order centroid method. The weights of the four criteria are the same as those in the AHP. The f_i in Table 4 shows the same trend as in Table 2, although individual values of f_i differ slightly between two methods.

Fuzzy Method

The fuzzy decision-making method consists of three main steps: (1) representation of the decision problem, (2) fuzzy set evaluation of the criteria and the alternatives, and (3) determination of the relative significance

Table 4. Relative significance factor of impact categories based on rank-order centroid method

	Time (0.439)	Area (0.311)	Irreversibility (0.146)	Uncertainty (0.104)	f_i
ARD	0.340	0.215	0.340	0.111	0.277
GW	0.215	0.340	0.215	0.340	0.267
OD	0.152	0.152	0.152	0.079	0.145
Eutro	0.033	0.033	0.033	0.016	0.032
Acid	0.054	0.054	0.054	0.054	0.054
POC	0.016	0.016	0.016	0.033	0.017
ET	0.079	0.111	0.079	0.152	0.097
HT	0.111	0.079	0.111	0.215	0.112

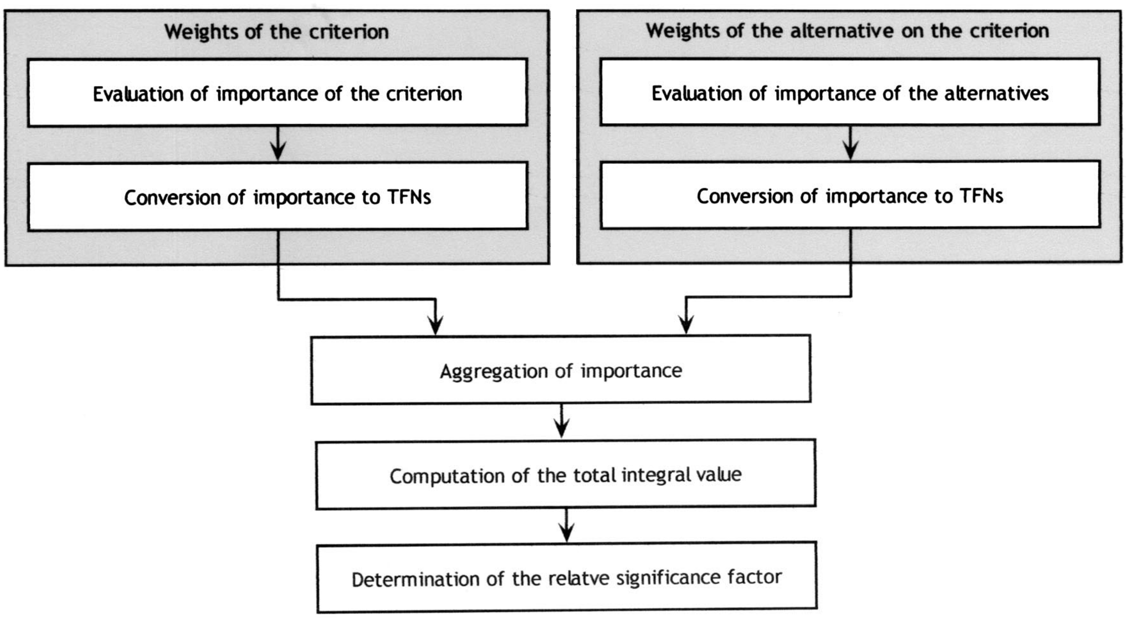

Figure 3. Steps for the determination of f_i based on the fuzzy method.

factor (Moon and Kang 1998). Figure 3 shows the procedure for the determination of f_i by the fuzzy method.

Fuzzy set evaluation. With the linguistic variables representing the weight of the criteria as importance and the weight of the alternatives (impact category) as the degree of appropriateness, term sets of the importance and appropriateness can be expressed as T (importance) = {VL, L, M, H, VH}, where VL = very low, L = low, M = medium, H = high, and VH = very high; and T (appropriateness) S = {VP, P, F, G, VG}, where VP = very poor, P = poor, F = fair, G = good, and VG = very good, respectively. Linguistic values are useful in expressing variables that are difficult to represent quantitatively. Fuzzy numbers can express linguistic values. Table 5 shows the triangular fuzzy numbers corresponding to each linguistic value for the determination of the weights of the criteria and the alternatives.

Table 5. Triangular fuzzy number corresponding to each linguistic value

Criteria	TFN	Alternatives
VL	(0, 0, 0.25)	VP
L	(0, 0.25, 0.5)	P
M	(0.25, 0.5, 0.75)	F
H	(0.5, 0.75, 1)	G
VH	(0.75, 1, 1)	VG

Ratings for the importance of the four criteria and the degree of appropriateness of the alternatives on the criteria are assigned based on judgments of the Korean LCA experts. The ratings for the criteria and the alter-

Table 6. Importance ratings for criteria

Criterion	Time	Area	Irreversibility	Uncertainty
Importance	VH	H	M	L

Table 7. Appropriateness ratings for alternatives

	Time	Area	Irreversibility	Uncertainty
ARD	VG	G	VG	F
GW	G	VG	G	VG
OD	G	G	G	F
Eutro	P	P	P	VP
Acid	P	P	P	P
POC	VP	VP	VP	P
ET	F	F	F	G
HT	F	F	F	G

Table 8. Fuzzy appropriateness index for the impact categories

Impact category	Fuzzy appropriateness index
ARD	(0.250, 0.547, 0.781)
GW	(0.219, 0.531, 0.813)
OD	(0.188, 0.453, 0.781)
Eutro	(0.000, 0.141, 0.375)
Acid	(0.000, 0.156, 0.406)
POC	(0.000, 0.016, 0.234)
ET	(0.094, 0.328, 0.641)
HT	(0.094, 0.328, 0.641)

natives are listed in Tables 6 and 7, respectively. The linguistic values in Tables 6 and 7 are transformed into triangular fuzzy numbers using the information in Table 5. Fuzzy appropriateness indices of the impact categories are then calculated, and the results are summarized in Table 8.

Determination of the relative significance factor. Assuming $\alpha = 0.5$, total integral values of the impact categories are calculated by substituting fuzzy appropriateness indices in Table 9, together with their normalized values. The total integral values of the impact categories are normalized to 1. The normalized total integral value is the weight of the impact category, which in turn becomes the relative significance of the impact category.

Results and Discussion

The f_i values based on three different methods are summarized in Table 10. The same order of significance of the impact categories between the AHP and the rank-order centroid method may be the result of the following: (1) experts may already recognize the order of significance of the impact categories at the time of pairwise comparison; and (2) those pairwise comparisons that do not meet the consistency requirements are already excluded from the f_i determination in case of the AHP. A minor difference in f_i between the rank-order centroid method and the fuzzy method may originate from the difference in transforming importance values of the impact categories into numbers: the former from the order information to crisp numbers, and the latter from the linguistic values to triangular fuzzy numbers.

Table 9. Total integral value and weight

	Total integral value	Weight
ARD	0.531	0.202
GW	0.523	0.199
OD	0.469	0.178
Eutro	0.164	0.062
Acid	0.180	0.068
POC	0.066	0.025
ET	0.348	0.132
HT	0.348	0.132

Table 10. Relative significance factor of impact categories

	AHP	Rank-order centroid	Fuzzy
ARD	0.250	0.277	0.202
GW	0.248	0.267	0.199
OD	0.161	0.145	0.178
Eutro	0.035	0.032	0.062
Acid	0.058	0.054	0.068
POC	0.024	0.017	0.025
ET	0.108	0.097	0.132
HT	0.116	0.112	0.132

A major difference between the AHP and the rank-order centroid method is the number of pairwise comparisons. The rank order centroid method requires not only performing a fewer number of pairwise comparisons but also simply assigning the order to the alternatives (here impact categories) in accordance with its significance. Weight is given automatically to each alternative once the rank of the alternative is determined; thus, there is no need for considering the consistency of the judgment on the alternatives rendered by the experts. In this sense, determination of the weight of each alternative is independent of the expert judgment. However, this does not mean that the weight is totally independent of the expert judgment. This is because the rank of alternative is determined by the expert judgment. Therefore, there is a linkage between weight of the alternative and the expert judgment through the ranking of the alternatives.

In contrast to this, there are many pairwise comparisons to be made in the AHP. The comparison should be performed not only between criteria but also between alternatives. It has been our experience that the return rate of AHP questionnaires decreased as the number of pairwise comparison increased. Furthermore, a higher degree of inconsistency was observed in the case of excessive numbers of pairwise comparisons to be made. This is probably because the experts replying to the questionnaire were bored and became less accurate and therefore less consistent as the comparison proceeded.

A major difference between the rank-order centroid method and the fuzzy method lies in the way of expressing the relative significance judged by experts as either a crisp number of a fuzzy number. The rank-order centroid method cannot express the degree of vagueness associated with the relative significance of the impact categories. On the other hand, the degree of vagueness can be expressed by the fuzzy method. Since significance is a subjective and relative concept rather than an objective and absolute concept, the fuzzy method can be a viable method in assigning weight to criteria and alternatives. In the fuzzy method, the ranking method of the fuzzy number is a critical issue in calculating the weight of the alternatives, and there is no single ranking method that is generally considered to be superior. This is a shortcoming of the fuzzy method used in this study.

One of the requirements for the weighting method to be viable is that the weighting results should be the same or similar among the different methods evaluated. If different approaches lead to different conclusions, the reasons for divergence need to be analyzed so that an appropriate method can be selected to fit the decision situation in question. In order to examine the correlation between the three MADM methods used for the determination of f_i, correlation coefficients of the f_i values between the AHP and the rank-order centroid method and between the rank-order centroid method and the fuzzy methods were calculated. The correlation coefficient between the AHP and the rank order centroid method was 0.994 and that between the rank-order centroid method and the fuzzy method was 0.929. Thus, there exists a strong relationship among the three different MADM methods evaluated here. These results indicate that determination of f_i by the same group of experts with the same goal in the decision-making structure will result in the same or a similar f_i as long as the expert's judgment on the degree of significance on the impact categories is similar.

Conclusions

The results from the three methods were very similar, and all three methods were considered to be useful for determining the relative significance factor of impact categories in systematic way. Key findings of this study are:

- Determination of f_i by the AHP, the rank-order centroid method and the fuzzy method all produced the same order of significance among the impact categories, although individual values of f_i varied slightly among the three methods.
- All three methods showed positive relationships. The correlation coefficient values indicate a higher degree of correlation among the three different methods.
- Determination of f_i by the same group of experts with the same goal in the decision-making structure will result in the same or a similar f_i as long as the experts' judgment on the degree of significance on the impact categories is similar.
- The rank-order centroid method reduces the number of pairwise comparisons by placing the alternatives in order, although it has inherent weakness over the fuzzy method in expressing the degree of vagueness associated with assigning weights to criteria and alternatives.
- The rank-order centroid method is considered a practical method for the determination of f_i because it is easier and simpler to use compared to the AHP and the fuzzy method.

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