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Fuzzy Multiple-Criteria Decision-Making Approach for Industrial Green Engineering

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ABSTRACT / This paper describes a fuzzy hierarchical analytic approach to determine the weighting of subjective judgments. In addition, it presents a nonadditive fuzzy integral technique to evaluate a green engineering industry case as a fuzzy multicriteria decision-making (FMCDM) problem. When the investment strategies are evaluated from various aspects, such as economic effectiveness, technical feasibility, and environmental regulation, it can be regarded as an FMCDM problem. Since stakeholders cannot clearly estimate each considered criterion in terms of numerical values for the anticipated alternatives/strategies, fuzziness is considered to be applicable. Consequently, this paper uses triangular fuzzy numbers to establish weights and anticipated achievement values. By ranking fuzzy weights and fuzzy synthetic utility values, we can determine the relative importance of criteria and decide the best strategies. This paper applies what is called a λ fuzzy measure and nonadditive fuzzy integral technique to evaluate the synthetic performance of green engineering strategies for aquatic products processors in Taiwan. In addition, we demonstrate that the nonadditive fuzzy integral is an effective evaluation and appears to be appropriate, especially when the criteria are not independent.

Along with technological and economic development, mass production has resulted in increasing waste, including hazardous emissions and toxic waste from manufacturing process. According to United States Environmental Protection Agency statistics, in 2000, over 400 million tons of hazardous waste emissions and industrial waste is processed annually worldwide. Furthermore, about 480 million tons of municipal waste is produced in daily life. Preserving the planet on which we live is an urgent challenge for our time.

Green engineering aims to reclaim industrial or municipal waste and is an increasingly important viewpoint, which also provides the opportunity for sustainable development of enterprise. In 1992, the United Nations Environmental Planning Board (UNEP) presented Agenda 21 of the Rio Declaration on Environment and Development as a guideline to improve sustainable development. In addition, in 1996 UNEP proposed the structure and approaches of sustainable development index. The United States developed 10 goals and a related sustainable development index for their country in the same year. The United Kingdom declared 120 sustainable development indices for their country in 1992. They then integrated these into 13 major indices to evaluate the performance of economic development, social investment, climate change, environmental quality and ecological conservation for their country in 1996 (Mendoza and Prabhu 2000).

KEY WORDS: Green engineering industry; Nonadditive fuzzy integral; Fuzzy multicriteria decision-making; λ fuzzy measure

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Environmental planning and decision-making in green engineering industries are essentially conflict analysis characterized by sociopolitical, environmental, and economic value judgments. Several alternatives/strategies have to be considered and evaluated in terms of many different criteria resulting in a vast body of data that are often inaccurate or uncertain.

In real world systems, the decision-making problems are very often uncertain or vague in a number of ways. Due to lack of information, the future state of the system might not be known completely. This type of uncertainty has long been handled appropriately by probability theory and statistics. However, in many areas of daily life, such as engineering, medicine, meteorology, manufacturing, and others, human judgment, evaluation, and decisions often employ natural language to express thinking and subjective perception. In these natural languages the meaning of words is often vague. The meaning of a word might be well defined, but when using the word as a label for a set, the boundaries within which objects do or do not belong to the set become fuzzy or vague.

Furthermore, human judgment of events may be significantly different based on individuals' subjective perceptions or personality, even using the same words. Fuzzy numbers are introduced to appropriately express linguistic variables. We will provide a more clear description of linguistic expression with fuzzy scale in a later section.

In this paper the fuzzy hierarchical analytic approach was used to determine the weights of criteria from subjective judgment, and a nonadditive integral technique was utilized to evaluate the performance of green engineering strategies for aquatic products processors in Taiwan. Traditionally, researchers have used additive techniques to evaluate the synthetic utilities of each criterion. In this article, we demonstrate that the nonadditive fuzzy integral is a good means of evaluation and appears to be more appropriate, especially when the criteria are not independent situations.

The conceptual development of green engineering is discussed in the next section, and the fuzzy hierarchical analytic approach and nonadditive fuzzy integral evaluation process for multicriteria decision-making (MCDM) problem are derived in the subsequent section. Then an illustrative example is presented, applying the MCDM methods for aquatic products processors in Taiwan, after which we discuss and show how the MCDM methods in this paper are effective. Finally, the conclusions are presented.

Concept Development of Green Engineering Thinking

Recently, environmental concerns have raised public awareness of environmental issues and are driving forces for regulation. The impact of regulation on the cost of production is expected to become an important determinant for the international competitiveness of industries. In response to cost pressures, industries have launched a number of initiatives aimed at improving efficiency and reducing environmental impact; reclaiming techniques are effective and economic approaches to enable enterprises to achieve goals of sustainable development.

When a consumer no longer wants to keep a product, any of the following options may be possible (Lave and others 1994, 1999), of which options 1–4 are kinds of green engineering (Simon 1992): (1) reuse (as with old furniture); (2) remanufacture (as with copier machines or automobile alternators); (3) recycle for the same use in a "closed loop" (as with asphalt pavement); (4) recycle into a lower valued use (as with plastics formed into park benches); (5) incinerate (as with burning paper to reclaim energy); (6) landfill (as with most municipal solid waste); and (7) discard directly to the environment (as with littering or dumping into the ocean).

Since the United Nations General Assembly proposed "Our Common Future" in 1987, the international social system began to take account of environmental and sustainable development issues. There have been many bilateral, multilateral, regional, and global agreements to provide environmental protection, and some of the important regulations are described in Appendix 1.

There is much evidence that environmental issues may affect business profits. In addition, all enterprises must take responsibility to value our resources by complying with regulations. Reclaiming of resources is an ecoefficient strategy and a paragon of sustainable development. According to our survey of the literature, several multicriteria analytic methods have been used to deal with environmental problems. The main approaches can be classified based on the type of decision model they used (Lahdelma and others 2000): (1) value or utility function-based methods, such as multiattribute utility theory (Keeney and Raiffa 1976, Merkhofer and Keeney 1987, Teng and Tzeng 1994, Tzeng and others 1996), AHP (Saaty 1980), DEA (Oral and others 1991), and the stochastic multiobjective acceptability analysis methods (Lahdelma and others 1998, Roy and others 1986); or (2) outranking methods such as ELECTRE (Siskos and Hubert 1983, Grassin 1986, Roy and Bouyssou 1986, Roy 1991, Hokkanen and others 1995, Hokkanen and Salminen 1997a, b, Salminen and others 1998), PROMETHEE I and II (Brans and Vincke 1985, Briggs and others 1990), and GFD (Caruso and others 1993).

Hierarchical Analytic Process and Evaluation Methods

In real MCDM problems, it is necessary to divide the process into distinct stages. First, based on a general problem statement, the various stakeholders are defined, typically including decision-makers, various interest groups affected by the decision, experts in the appropriate fields, as well as planners and analysts responsible for the preparations and managing the process. The overall objective will be set up in this stage. Second, based on various points of view from stakeholders, the problems can be categorized into distinct aspects. Third, defining alternatives/strategies and criteria, a discrete MCDM problem consisting of a finite set of alternatives/strategies can be evaluated in terms of multicriteria. Finally, choosing a suitable method to measure the criteria can help the evaluators and analysts to process the evaluating cases.

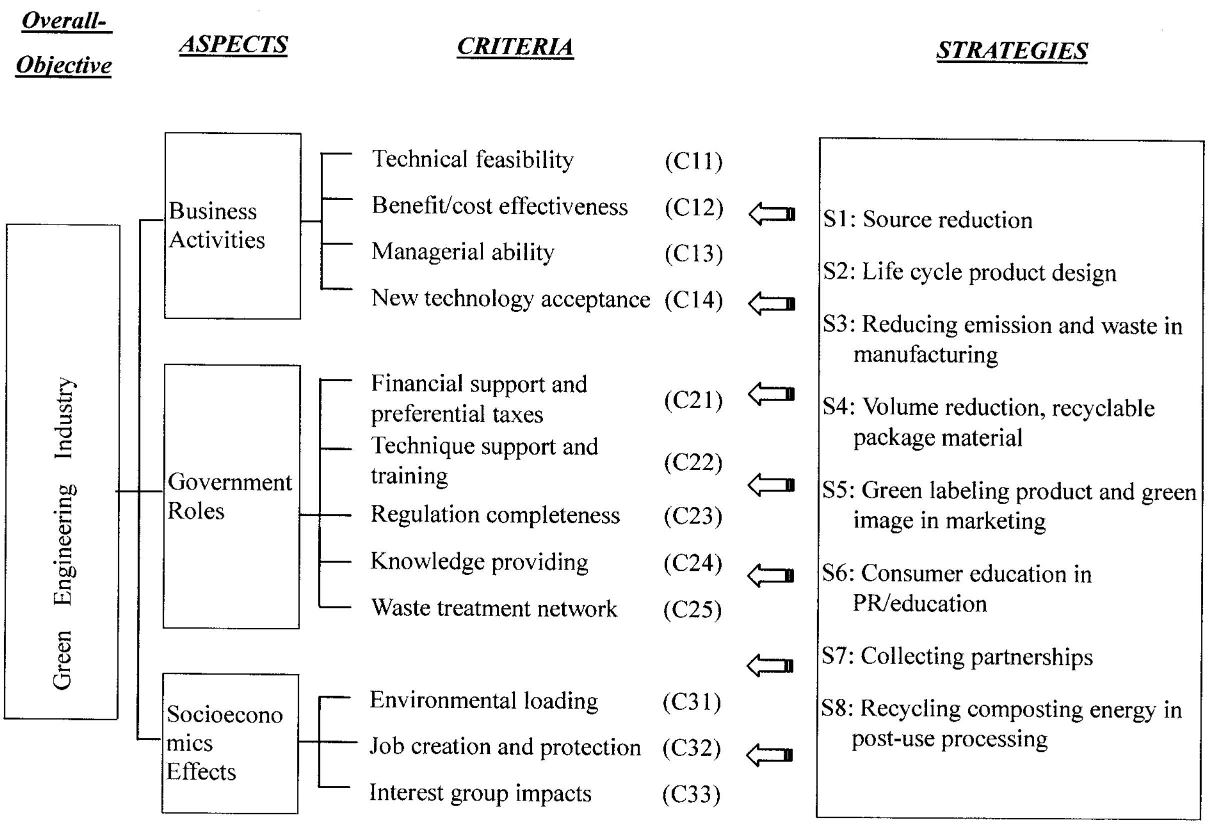

Figure 1. Hierarchical system in green engineering industry.

Building a Hierarchical System for Green Engineering Industry

First of all, we establish a hierarchy system of green engineering industry for analysis and evaluation through scenario writing and brainstorming, as shown in Figure 1. Phase 1 includes our overall objectives. Second, we consider three aspects for achieving goals in phase 2, including business activities, government roles and socioeconomic effects. Third, we consider four criteria in business activities, five criteria in government roles, and three criteria in socioeconomic effects with respect to our consideration aspects that are evaluated and selected outranking listed in phase 3. All criteria considered are measured by evaluators, consisting of individuals with different viewpoints. Finally, the strategies of green engineering to carry on the business of participating companies are listed in phase 4. The postuse process of products with eight strategies from source materials is considered to meet green engineering concepts. Each enterprise will choose the strategies based on technical feasibility, financial status, managerial ability, relevant business situation, etc. The definitions of relevant criteria and strategies are listed in Table 1.

Determination of Evaluation Criteria Weights

Because the evaluation of criteria entails diverse meanings, we cannot assume that each evaluation criterion is of equal importance. There are many methods that can be employed to determine weights (Hwang and Yoon 1981), such as the eigenvector method, weighted least square method, entropy method, AHP, as well as linear programming techniques for multidimension of analysis preference (LINMAP). The selection of method depends on the nature of the problems. We use the fuzzy geometric mean method to determine the criteria weights in this paper.

Saaty (1980) originally introduced the Analytic Hierarchy Process (AHP) to systematically cope with complex problems in social system. He used the principal eigenvector of the comparison matrix to find the comparative weight among the criteria of the hierarchy systems. If we wish to compare a set of n criteria pairwise according to their relative importance (weights), then denote the criteria by $C_1, C_2, \ldots, C_n$ and their

Table 1. Definitions of criteria and strategies in green engineering industry

	Description
Criterion	
C11. Technical feasibility	To measure the degree of reclaim technique
C12. Benefit–Cost effectiveness	To measure the benefit–cost effectiveness from leading reclaim technique, including the value-increasing of new products and reduction of power expenditure and waste treatment costs, etc.
C13. Managerial ability	To measure who possesses the managerial ability in technique of waste treatment and reclamation.
C14. New technology acceptance	To measure the degree of acceptance of all inner members about reclaim technique in waste treatment and recovery that leads to company.
C21. Financial support and preferential taxes	To encourage business to engage in reclaiming the waste from process or material.
C22. Technique support and training	To measure the degree of government to provide the reclaim technique and knowledge in waste that will enhance business competence.
C23. Regulation completeness	To indirectly encourage business to develop and lead in reclamation techniques; it also gives protection to the legitimate companies.
C24. Knowledge providing	To hold technical seminars and publish (by government or organization) to provide knowledge of reclamation techniques in waste.
C25. Waste treatment network	To provide the channel of waste treatment that will prevent and reduce environment damage to ensure sustainable development.
C31. Environmental loading	To measure the degree of loading from enterprise or municipal waste, including water waste, waste liquid, viscera, mud, fishbone, shell, in addition to the offensive smell of fish in aquatic products processing.
C32. Job creation and protection	To measure contributions to the community from enterprise.
C33. Interest groups impacts	To include the protest by civil organizations, or residents of the impact area for pollution accident.
Strategies	
S1. Source reduction	Material and source reduction in the early part of product manufacturing.
S2. Life cycle product design	Expand product lifecycles in design stage.
S3. Reducing emission and waste in manufacturing	Emission and waste reduction in manufacturing process.
S4. Volume reduction, recyclable package material	Volume reduction, using recyclable package material.
S5. Green labeling product and green image in marketing	Produce green labeling of product and establish green image in marketing will encourage consumer to buy and use it.
S6. Consumer education in PR/education	Green label products will help consumer, to value resources
S7. Collecting partnerships	Establish good collecting partnerships and complete recycling network.
S8. Recycling composting energy in postuse processing	Develop new reclaiming technology transfer the waste that from produce and post-used process to new product, it will create new value to originally products and also might bring new niche to industry.

weights by $w_1, w_2, \ldots, w_n$. If $\boldsymbol{w} = (w_1, w_2, \ldots, w_n)^T$ is given, the pairwise comparisons may be represented by matrix $\boldsymbol{A}$ of the following formulation:

$$(\boldsymbol{A} - \lambda_{\max}\boldsymbol{I})\boldsymbol{w} = 0 \tag{1}$$

Equation 1 denotes that $\boldsymbol{A}$ is the matrix of pairwise comparison values derived by intuitive judgment for ranking order. The procedure for AHP can be summarized in four steps, as follows:

Step 1. Set up the decision system by decomposing the problem into a hierarchy of interrelated elements.

Step 2. Generate input data consisting of pairwise comparative judge of decision elements.

Step 3. Synthesize the judgment and estimate the relative weight.

Step 4. Determine the aggregating weights of the decision elements to arrive at a set of ratings for the alternatives/ strategies.

Obtaining Synthetic Utility Value

The evaluators choose a performance value for each participating company based on their subjective judgments. This way of estimating the achievement level of each criterion in each strategy can use the methods of fuzzy theory for treating the fuzzy environment.

Fuzzy number. Since Zadeh (1965) proposed the fuzzy set theory and Bellman and Zadeh (1970) subsequently described the decision-making methods in fuzzy environments, an increasing number of studies have dealt with uncertain fuzzy problems by applying fuzzy set theory. Similarly, this study includes fuzzy decision-making theory, considering the possible fuzzy subjective judgment during evaluation process.

According to Dubois and Prade (1978), a fuzzy number $\tilde{A}$ is a fuzzy subset of a real number, and its membership function is $\mu_{\tilde{A}}(x)$: $R \rightarrow [0,1]$, where x represents the criterion and is described by the following characteristics: (1) $\mu_{\tilde{A}}(x)$ is a continuous mapping from R to the closed interval [0,1]; (2) $\mu_{\tilde{A}}(x)$ is a convex fuzzy subset; and (3) $\mu_{\tilde{A}}(x)$ is the normalization of a fuzzy subset, which means that there exists a number x_0 such that $\mu_{\tilde{A}}(x_0) = 1$.

According to the characteristics of triangular fuzzy numbers and the extension principle put forward by Zadeh (1975), the operational laws of two triangular fuzzy numbers, $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{B} = (b_1, b_2, b_3)$, are as follows:

1. Addition of two fuzzy numbers $\oplus$.

$$(a_1, a_2, a_3) \oplus (b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \quad (2)$$

2. Subtraction of two fuzzy numbers Θ

$$(a_1, a_2 a_3)\ \Theta\ (b_1, b_2, b_3) = (a_1 - b_3, a_2 - b_2, a_3 - b_1) \quad (3)$$

3. Multiplication of two fuzzy numbers $\otimes$

$$(a_1, a_2, a_3) \otimes (b_1, b_2, b_3) \cong (a_1 b_1, a_2 b_2, a_3 b_3) \quad (4)$$

4. Multiplication of any real number k and a fuzzy number $\otimes$

$$k \otimes (a_1, a_2, a_3) = (ka_1, ka_2, ka_3) \quad (5)$$

5. Division of two fuzzy numbers $\varnothing$

$$(a_1, a_2, a_3) \varnothing (b_1, b_2, b_3) \cong (a_1/b_3, a_2/b_2, a_3/b_1) \quad (6)$$

Linguistic variables. According to Zadeh (1975), it is very difficult for conventional quantification to express reasonably those situations that are overtly complex or hard to define; thus the notion of a linguistic variable is necessary in such situations. A linguistic variable is a variable whose values are words or sentences in a natural or artificial language, and we use this kind of expression to compare two green engineering criteria by linguistic variables in a fuzzy environment as "absolutely important," "very strongly important," "essentially important," "weakly important," and "equally important" with respect to a fuzzy five-level scale. The use of linguistic variables is currently widespread, and the linguistic effect values of strategies found in this paper are primarily used to assess the linguistic ratings given by evaluators. Furthermore, linguistic variables are used as a way to measure the performance value of green engineering strategies for each criterion as "very low," "low," "fair," "high," and "very high." In this paper we employ the triangular fuzzy numbers to express the fuzzy scale as above.

Fuzzy weights for the hierarchy process. Buckley (1985) was the first to investigate fuzzy weights and the fuzzy utility for the AHP technique, extending AHP by the geometric mean method to derive the fuzzy weights. In Saaty (1980), if $\mathbf{A} = [a_{ij}]$ is a positive reciprocal matrix, then the geometric mean of each row r_i can be calculated as $r_i = \left(\prod_{j=1}^{m} a_{ij}\right)^{1/m}$. Here Saaty defined λ_{max} as the largest eigenvalue of $\mathbf{A}$ and the weight w_i as the component of the normalized eigenvector corresponding to λ_{max}, where $w_i = r_i/(r_1 + \ldots + r_m)$.

Buckley (1985) considered a fuzzy positive reciprocal matrix $\tilde{\mathbf{A}} = [\tilde{a}_{ij}]$, extending the geometric mean technique to define the fuzzy geometric mean of each row $\tilde{r}_i$ and fuzzy weight $\tilde{w}_i$ corresponding to each criterion as follows:

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \cdots \otimes \tilde{a}_{im})^{1/m};$$
$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \cdots \oplus \tilde{r}_m)^{-1} \quad (7)$$

Ranking the fuzzy measure and aggregation. Sugeno (1974) introduced the concepts of fuzzy measure and fuzzy integral, generalizing the usual definition of a measure by replacing the usual additive property with a weaker requirement, i.e., the monotonicity property with respect to set inclusion. In this section, we give a short introduction to some notions from the theory of fuzzy measure and fuzzy integral. For a more detailed account, refer to Dubois and Prade (1980), Grabisch (1995), Hougaard and Keiding (1996), among others.

Definition 1. Let X be a measurable set that is endowed with properties of σ-algebra, where $\aleph$ is all subsets of X. A fuzzy measure g, defined on the measurable space $(X, \aleph)$, is a set function g: $\aleph \rightarrow [0,1]$, which satisfies the following properties: (1) $g(\phi) = 0$, $g(X) = 1$ (boundary conditions); (2) $\forall A, B \in \aleph$, if $A \subseteq B$ then $g(A) \leq g(B)$ (monotonicity); (3) for every sequence of subsets of X, if either $A_1 \subseteq A_2 \subseteq \cdots$ or $A_1 \supseteq A_2 \supseteq \cdots$, then $\lim_{i\to\infty} g(A_i) = g(\lim_{i\to\infty} A_i)$ (continuity).

As in the above definition, $(X, \aleph, g)$ is said to be a fuzzy measure space. Furthermore, as a consequence of the monotonicity condition, we can obtain:

$$\begin{cases} g(A \cup B) \geq \max\{g(A), g(B)\} \\ g(A \cap B) \leq \min\{g(A), g(B)\} \end{cases} \quad (8)$$

while the two strict cases of measure g as

$$\begin{cases} g(A \cup B) = \max\{g(A), g(B)\} \\ g(A \cap B) = \min\{g(A), g(B)\} \end{cases} \quad (9)$$

are called possibility measure and necessity measure, respectively. We have summarized some definitions and properties of these topics in Appendix 2.

Definition 2. Let $(X, \aleph, g)$ be a fuzzy measure space. Then the Choquet integral of a fuzzy measure g: $\aleph \rightarrow [0,1]$ with respect to a simple function h is defined by

$$\int h(x) \cdot dg \cong \sum_{i=1}^{n} [h(x_i) - h(x_{i-1})] \cdot g(A_i) \quad (10)$$

with the same notions as above, and $h(x_{(0)}) = 0$.

From the beginning of the application of fuzzy measures and fuzzy integrals to multicriteria evaluation problems, it has been thought there was dependence between criteria. Keeney and Raiffa (1976) advocated the multiattribute multiplicative utility function, called the nonadditive multicriteria evaluation technique, to refine situations that do not conform to the assumption of independence between criteria (Ralescu and Adams 1980, Chen and Tzeng 2001, Chen and others 2000). In this paper, we apply Keeney's nonadditive multicriteria evaluation technique using Choquet integrals to derive the fuzzy synthetic utilities of each strategy for criteria as follows.

Let g be a fuzzy measure that is defined on a power set $P(\text{x})$ and satisfies definition 1 above. The following characteristic is evidently,

$$\forall A, B \in P(X), A \cap B = \phi \Rightarrow g_\lambda(A \cup B) = g_\lambda(A) + g_\lambda(B) + \lambda g_\lambda(A) g_\lambda(B) \quad for \quad -1 \leq \lambda < \infty \quad (11)$$

where set $X = \{x_1, x_2, \ldots, x_n\}$, and the density of fuzzy measure $g_i = g_\lambda(\{x_i\})$ can be formulated as follows:

$$g_\lambda(\{x_1, x_2, \cdots, x_n\}) = \sum_{i=1}^{n} g_i + \lambda \sum_{i_1=1}^{n-1} \sum_{i_2=i_1+1}^{n} g_{i_1} \cdot g_{i_2} + \cdots + \lambda^{n-1} \cdot g_1 \cdot g_2 \cdots g_n = \frac{1}{\lambda} \left| \prod_{i=1}^{n} (1 + \lambda \cdot g_i) - 1 \right| \quad for \quad -1 \leq \lambda < \infty \quad (12)$$

For an evaluation case with two criteria, A and B, one of three cases as following will be sustained, based on the above properties:

Case 1: if $\lambda > 0$, i.e., $g_\lambda(A \cup B) > g_\lambda(A) + g_\lambda(B)$, then this implies A and B have multiplicative effect.

Case 2: if $\lambda = 0$, i.e., $g_\lambda(A \cup B) = g_\lambda(A) + g_\lambda(B)$, then this implies A and B have additive effect.

Case 3: if $\lambda < 0$, i.e., $g_\lambda(A \cup B) < g_\lambda(A) + g_\lambda(B)$, then this implies A and B have substitutive effect.

Let h be a measurable set function defined on the fuzzy measurable space $(X, \aleph)$ and suppose that $h(x_1) \geq h(x_2) \geq \cdots \geq h(x_n)$, then the fuzzy integral of fuzzy measure $g(\cdot)$ with respect to $h(\cdot)$ can be defined as follows (Ishii and Sugeno 1985).

$$\int h \cdot dg = h(x_n) \cdot g(H_n) + [h(x_{n-1}) - h(x_n)] \cdot g(H_{n-1}) + \cdots + [h(x_1) - h(x_2)] \cdot g(H_1) = h(x_n) \cdot [g(H_n) - g(H_{n-1})] + h(x_{n-1}) \cdot [g(H_{n-1}) - g(H_{n-2})] + \cdots + h(x_1) \cdot g(H_1) \quad (13)$$

where $H_1 = \{x_1\}$, $H_2 = \{x_1, x_2\}, \cdots, H_n = \{x_1, x_2, \cdots, x_n\} = X$. In addition, if $\lambda = 0$ and $g_1 = g_2 = \cdots = g_n$ then $h(x_1) \geq h(x_2) \geq \; \geq h(x_n)$ is not necessary.

In order to clarify the operation of the fuzzy integral technique, we give numerical example in Appendix 3.

On the other hand, the result of fuzzy synthetic decisions reached by each alternative is a fuzzy number. Therefore, it is necessary that the nonfuzzy ranking method for fuzzy numbers be employed during the comparison of the strategies. In previous work, the procedure of defuzzification has been to locate the best nonfuzzy performance (BNP) value. Methods of such defuzzified fuzzy ranking generally include the mean of maximal, center of area (COA), and α-cut (Zhao and Govind 1991, Tsaur and others 1997, Tang and others 1999). Utilizing the COA method to determine the BNP is simple and practical, and there is no need to introduce the preferences of any evaluators. The BNP value of the triangular fuzzy number (LR_i, MR_i, UR_i) can be found by the following equation:

$$BNP_i = [(UR_i - LR_i) + (MR_i - LR_i)]/3 + LR_i, \; \forall i \quad (14)$$

For those reasons, the COA method is used in this paper to rank the order of importance of each criterion. According to the value of the derived BNP, the evaluation of each green engineering strategy can then proceed.

In this paper when the criteria are not necessary mutually independent, we use factor analysis and the nonadditive fuzzy integral technique to find the synthetic utilities of green engineering strategies, and to observe the order of the synthetic utilities in different λ values.

Illustrative Example

In this section we take an illustrative example for evaluating the green engineering industry to demon-

Table 2. Criteria weights for evaluating green engineering industry[a]

Aspects and criteria	Local weights	Overall weights	BNP
Business activities	(0.103,0.311,0.917)		
Technical feasibility	(0.102,0.337,1.178)	(0.011,0.105,1.080)	0.398 (2)
Benefit/Cost effectiveness	(0.086,0.307,1.032)	(0.009,0.096,0.946)	0.350 (3)
Managerial ability	(0.050,0.185,0.731)	(0.005,0.058,0.670)	0.244 (8)
New technology acceptance	(0.040,0.171,0.653)	(0.004,0.053,0.598)	0.219 (10)
Government roles	(0.128,0.373,1.080)		
Financial support and preferential taxes	(0.036,0.133,0.444)	(0.005,0.049,0.480)	0.178 (12)
Technique support and training	(0.049,0.169,0.537)	(0.006,0.063,0.580)	0.216 (11)
Regulation completeness	(0.087,0.251,0.738)	(0.011,0.094,0.797)	0.301 (5)
Knowledge providing	(0.066,0.201,0.639)	(0.008,0.075,0.690)	0.258 (7)
Waste treatment network	(0.085,0.246,0.735)	(0.011,0.092,0.793)	0.299 (6)
Social economics effects	(0.109,0.316,0.945)		
Environmental loading	(0.162,0.454,1.288)	(0.018,0.143,1.218)	0.460 (1)
Job creation and protection	(0.072,0.206,0.687)	(0.008,0.065,0.649)	0.241 (9)
Interest groups impacts	(0.108,0.340,0.954)	(0.012,0.107,0.902)	0.340 (4)

[a]Parentheses denote the order of importance (BNP weights) of each criterion.

strate that these methods of fuzzy measure and nonadditive fuzzy integral provide a good evaluation and appear to be more appropriate, especially when the criteria are not independent situations in a fuzzy environment. This section is divided into five subsections: (1) problem description, (2) determining of evaluation criteria weights, (3) determining the performance matrix, (4) calculating the nonadditive fuzzy synthetic utilities, and (5) discussions.

Problem Description

The aquatic products industry is a branch of the food products industry. There are abundant fishery resources in Taiwan because of its geographical features, and aquatic products are an important dietary resource in daily life. However, for example, about 50% of harvested fish material is not edible, and how to reclaim this waste is an important challenge. In Japan, special techniques are used to process the waste from aquatic products for extracts such as fish oil, fish meal, and fish solution, which are used to make health food, forage additives, and so on, in addition to uses in agriculture and medical science.

There are about 600 aquatic products processors in Taiwan based on the Fishery Annual Report in 1998, the majority of which are small-sized enterprises. Only some of them have engaged in reclaiming waste from processing aquatic products such as fish, shrimp, and shellfish. In this study, we apply the fuzzy AHP approach and the nonadditive fuzzy integral technique to evaluate the performance of green engineering strategies, reviewing ten companies as samples of aquatic products processors in this island.

Determining of Evaluation Criteria Weights

First, we establish the green engineering decision hierarchy frame shown in Figure 1, where the preliminary classification is comprised of aspects involving business, government, and socioeconomic dimensions, with 12 criteria selected. Secondly, we have 15 evaluators, including staff from the government sector who are in charge of sustainable development, academic experts, company executives of aquatic products processors, members of environmental interest groups, and residents. We integrate their subjective judgments to develop the fuzzy criteria weights with respect to aspects by the fuzzy geometric mean method as in equation 7. We then derive the final fuzzy weights and nonfuzzy BNP values corresponding to each criterion, as shown in Table 2.

Determining the Performance Matrix

To determine the performance value of each strategy, the evaluators can define their own individual range for the linguistic variables employed in this paper according to their subjective judgments within a fuzzy scale. Under future uncertainties, the anticipated performance values of unquantifiable criteria cannot be specified with qualitative numerical data in qualitative evaluation pertaining to the possible achievement value of each strategy.

Let $\tilde{h}_{ij}^{k}$ represent the fuzzy performance score by the kth evaluator of the ith strategy under the jth criterion. Since the perception of each evaluator varies according to individual experience and knowledge, and the definitions of linguistic variables also vary, we employ the fuzzy geometric mean method to integrate the fuzzy

Table 3. Fuzzy performance score of green engineering strategies with respect to criteria

Strategy	Criteria				
	C11	C12	C13	C14	C21
S1. Source reduction	(1.55,2.65,4.91)	(1.63,3.06,5.30)	(2.83,4.91,6.94)	(2.27,4.44,6.49)	(1.12,3.16,5.17)
S2. Life cycle product design	(2.81,4.99,7.06)	(3.71,5.91,7.67)	(2.03,4.22,6.27)	(2.95,5.16,7.24)	(1.12,2.03,4.22)
S3. Reducing emission and waste in manufacturing	(2.39,4.59,6.65)	(1.25,2.39,4.59)	(1.25,2.67,4.83)	(1.25,2.67,4.83)	(1.00,1.93,4.08)
S4. Volume reduction, recyclable package material	(2.95,5.16,7.24)	(2.27,4.44,6.49)	(2.79,5.08,7.18)	(4.44,6.49,8.35)	(1.31,2.21,4.47)
S5. Green labeling product and green image in marketing	(3.11,5.34,7.42)	(3.78,5.96,7.87)	(2.14,4.36,6.43)	(1.73,3.47,5.62)	(1.00,1.25,3.32)
S6. Consumer education in PR/ Education	(2.67,4.83,6.88)	(3.30,5.44,7.48)	(3.41,5.57,7.48)	(2.98,5.08,7.12)	(1.46,2.90,5.12)
S7. Collecting partnerships	(2.67,4.83,6.88)	(1.82,4.01,6.07)	(2.25,4.51,6.60)	(1.93,4.08,6.12)	(1.25,2.39,4.59)
S8. Recycling composting energy in postuse processing	(3.78,5.96,7.87)	(3.13,5.26,7.30)	(3.30,5.44,7.48)	(3.68,5.72,7.74)	(1.82,4.01,6.07)

performance score $\tilde{h}_{ij}$ for m evaluators, as shown in Table 3. This is,

$$\tilde{h}_{ij} = (\tilde{h}_{ij}^{1} \otimes \cdots \otimes \tilde{h}_{ij}^{m})^{1/m} \quad (15)$$

Furthermore, we employ the COA defuzzification procedure to compute the BNP values of fuzzy performance score $\tilde{h}_{ij}$, as shown in Table 4.

Calculating the Nonadditive Fuzzy Synthetic Utilities

When the criteria are not necessarily mutually independent, in order to drive the synthetic utilities, we first exploit the factor analysis technique to extract the criteria in four common factors. The first factor includes five criteria: technical feasibility (C11), benefit–cost effectiveness (C12), financial support and preferential taxes (C21), technique support and training (C22), and environmental loading (C31). The second factor includes three criteria: managerial ability (C13), new technology acceptance (C14), and knowledge providing (C24). The third factor also includes three criteria: waste treatment network (C25), job creation and protection (C32), and interest groups impacts (C33). The final factor includes only one criterion, regulation completeness (C23). The criteria within the same factor are not independent; rather they are a nonadditive measurement case, so we utilize the nonadditive fuzzy integral technique to find the synthetic utilities of each strategy within the same factor. On the other hand, there is mutual independence between factors, and the measurement is an additive case, so we utilize the additive aggregate method to conduct the synthetic utilities (see Figure 2). A more explicit procedure for conducting final synthetic utilities is summarized in Appendix 4.

Futhermore, we have conducted the synthetic utilities of each strategy using different λ values, with the results as shown in Table 5.

Discussions

Earlier we introduced the λ value representing the properties of substitution between criteria, where λ values range from −1 to a positive infinite value (∞). We can find the variation of synthetic utilities in different λ value is given. For each strategy, the synthetic utilities decrease with respect to λ and rapidly decrease in $\lambda = 0$. Furthermore, situations where $\lambda < 0$ are substitutive effect cases, for example, where $\lambda = -1$. In this case we outrank the fuzzy synthetic utilities, as follows: S7>S3>S1>S4>S5>S6>S8>S2. Moreover, when $\lambda = 0$, it is an additive effect case, and we outrank the fuzzy synthetic utilities, as follows: S7>S5>S3>S6>S1>S4>S8>S2. Finally, when $\lambda > 0$, there are multiplicative effect cases, for example, where $\lambda = 5$. Then we have different outranking fuzzy synthetic utilities, as follows: S5>S7>S3>S6>S2>S8>S1>S4, where *A*>*B* means A outranks B (see Table 5).

In addition, if the criteria are independent in a fuzzy environment, conducting the fuzzy synthetic utilities by

Table 3. (Continued)

Criteria						
C22	C23	C24	C25	C31	C32	C33
(3.30,5.44,7.48)	(1.25,2.67,4.83)	(3.24,5.39,7.30)	(3.30,5.44,7.48)	(4.29,6.33,8.35)	(1.00,1.12,3.16)	(1.00,1.55,3.68)
(1.39,3.50,5.53)	(1.92,3.33,5.62)	(2.03,4.22,6.27)	(1.39,2.52,4.75)	(2.95,5.16,7.24)	(1.00,1.55,3.68)	(1.12,2.27,4.44)
(2.39,4.59,6.65)	(3.47,5.62,7.67)	(2.14,4.36,6.43)	(4.22,6.27,8.14)	(4.36,6.43,8.14)	(2.53,4.67,6.71)	(2.14,4.36,6.43)
(1.25,2.39,4.59)	(1.12,2.27,4.44)	(3.68,5.72,7.74)	(5.16,7.24,8.56)	(1.39,2.52,4.75)	(1.82,3.22,5.48)	(1.39,3.13,5.26)
(2.81,4.99,7.06)	(3.30,5.44,7.48)	(3.59,5.76,7.67)	(3.91,6.11,7.87)	(1.54,3.00,5.25)	(1.00,1.55,3.68)	(2.14,3.91,6.11)
(2.33,4.14,6.27)	(3.78,5.96,7.87)	(3.65,5.81,7.87)	(3.65,5.81,7.87)	(1.25,1.92,4.14)	(1.00,1.39,3.50)	(1.12,1.46,3.62)
(3.11,5.34,7.42)	(4.08,6.12,8.14)	(3.87,5.92,7.94)	(5.44,7.48,8.78)	(4.08,6.12,8.14)	(1.46,2.90,5.12)	(2.95,5.16,7.24)
(4.44,6.49,8.35)	(5.08,7.12,8.78)	(4.44,6.49,8.35)	(3.11,5.34,7.42)	(2.81,4.99,7.06)	(1.92,3.33,5.62)	(1.72,3.53,5.72)

Table 4. BNP values of fuzzy performance score with respect to criteria

	BNP values of criteria											
Strategy	C11	C12	C13	C14	C21	C22	C23	C24	C25	C31	C32	C33
S1. Source reduction	3.035	3.328	4.894	4.399	3.148	5.406	2.914	5.309	5.406	6.321	1.758	2.077
S2. Life cycle product design	4.953	5.766	4.175	5.118	2.455	3.473	3.620	4.175	2.884	5.118	2.077	2.608
S3. Reducing emission and waste in manufacturing	4.544	2.741	2.914	2.914	2.336	4.544	5.589	4.312	6.210	6.311	4.638	4.312
S4. Volume reduction, recyclable package material	5.118	4.399	5.012	6.424	2.665	2.741	2.608	5.714	6.987	2.884	3.505	3.260
S5. Green labeling product and green image in marketing	5.290	5.870	4.312	3.608	1.856	4.953	5.406	5.676	5.963	3.265	2.077	4.054
S6. Consumer education in PR/Education	4.793	5.406	5.489	5.059	3.162	4.247	5.870	5.779	5.779	2.436	1.962	2.065
S7. Collecting partnerships	4.793	3.965	4.453	4.043	2.741	5.290	6.111	5.909	7.232	6.111	3.162	5.118
S8. Recycling composting energy in postuse processing	5.870	5.229	5.406	5.714	3.965	6.424	6.992	6.424	5.290	4.953	3.620	3.654

the simple additive weight method is traditionally used. This method is especially appropriate to employ in independent criteria situations. In this paper we also compute the fuzzy synthetic utilities by the simple additive weight method and obtain a different outranking, as follows: S5>S7>S1>S3>S2>S8>S4>S6.

Evaluating and planning the strategies and criteria in the green engineering industry or in another real MCDM problem can result in a vast body of data that are often inaccurate or uncertain and come from the subjective judgment by various stakeholders who are the evaluators. Moreover, despite the correlation between different criteria, the conventional MCDM methods are based on the assumption of independence among criteria within the evaluating system, with the subsequent decision-making activities being performed in an additive process. However, in such complex MCDM problems, we can show through a factor analysis statistical approach that the criteria are not independent. Therefore, we demonstrate that the nonadditive fuzzy integral is more appropriate for real-world MCDM problems.

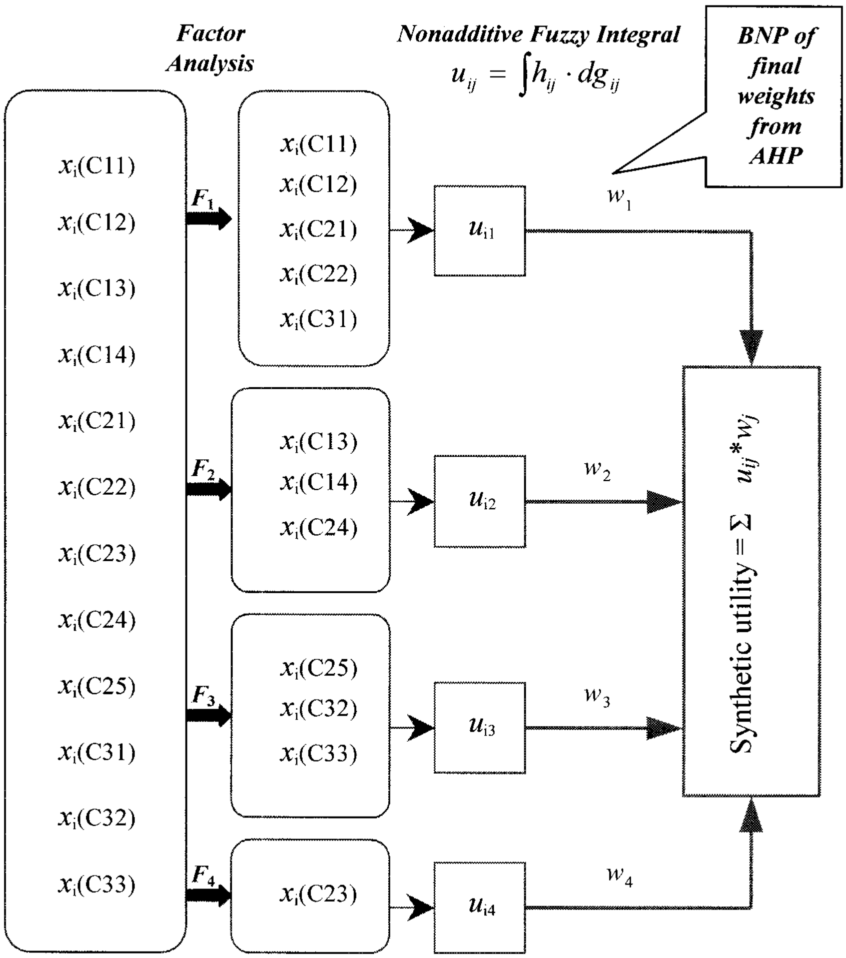

Figure 2. Synthetic utilities with additive and nonadditive measurements.

Conclusions

Generally, the green engineering industry provides environmental planning and decision-making problems that are essentially conflict analyses characterized by sociopolitical, environmental, and economic value judgments. Several alternatives/strategies have to be considered and evaluated in terms of many different criteria, resulting in a vast body of data that are often inaccurate or uncertain. We introduce fuzzy numbers to express linguistic variables that consider the possible fuzzy subjective judgment of the evaluators. Furthermore, the fuzzy geometric mean technique is an effective method to obtain the final fuzzy weights of each criterion.

In this study, we successfully demonstrate the nonadditive fuzzy integral technique to deal with the decision-making problem if the criteria are not independent. Actually, in real MCDM problems, where the criteria are not necessarily mutually independent, if we employ the simple additive aggregate method (also called the weighted mean method) to derive the final synthetic utility, it will overestimate when the criteria have substitutive properties, or underestimate when the criteria have multiplicative properties. We provided two examples earlier to illustrate the λ value for the property of the criteria, which will result in a different ranking order.

In this paper, we employ fuzzy synthetic utilities to rank green engineering strategies. The strategy called "establish good collecting partnerships and complete recycling network (S7)" is the best strategy when enterprise would like to engage in green engineering if the criteria considered are substitutive and independent. On the other hand, the strategy called "produce green labeling product and establish green image exhibiting in marketing (S5)" is the best strategy when the criteria considered are multiplicative. This is a useful information for new businesses in this industry. Furthermore, if we want to evaluate the individual synthetic utility of participating companies, the nonadditive fuzzy integral technique is an effective method.

Table 5. Synthetic utilities with λ values

λ	S1	S2	S3	S4	S5	S6	S7	S8
−1.0	13.377	8.764	13.497	12.197	11.567	10.667	14.126	9.046
−0.5	4.297	3.461	4.780	3.962	5.210	4.277	5.353	3.644
−0.0	3.679	3.104	4.226	3.410	4.710	3.763	4.755	3.226
0.5	3.331	2.905	3.915	3.097	4.427	3.472	4.421	2.991
1.0	3.091	2.768	3.699	2.881	4.231	3.270	4.191	2.830
3.0	2.560	2.468	3.223	2.401	3.795	2.821	3.686	2.476
5.0	2.284	2.312	2.974	2.150	3.566	2.586	3.425	2.293
10.0	1.923	2.111	2.647	1.821	3.265	2.277	3.086	2.056
20.0	1.604	1.930	2.353	1.528	2.993	2.001	2.787	1.848
40.0	1.341	1.782	2.108	1.285	2.765	1.773	2.544	1.679
100.0	1.078	1.629	1.853	1.040	2.528	1.540	2.299	1.511
150.0	0.990	1.578	1.766	0.957	2.448	1.462	2.218	1.457
200.0	0.935	1.545	1.710	0.905	2.395	1.412	2.167	1.422
SAW[a]	4.041	2.298	4.020	2.125	4.467	2.073	4.252	2.227

[a]The synthetic utilities by simple additive weight (SAW) method with respect to strategies

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Appendix 1

We describe some of important environmental regulations as follows:

1. Basel Convention—including 52 nations, the majority of the Organization of Economic Corporation and Development (OECD) nations, signed in 1989 and taking effect in 1992, to prohibit OECD nations from exporting waste for final disposal or recycling treatment by non-OECD nations.
2. Rio Declaration—the majority of nations who participated in the United Nations Conference on Environment and Development (UNCED) signed in 1992. This declaration clearly expressed the principle of rights and responsibilities for environmental issues.
3. The Framework Convention on Climate Change—the majority of nations who participated in the UNCED signed in 1992. This convention includes 5 principles and 10 commitments for waste emission standards that would contribute to the greenhouse effect, such as carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFC_5), nitrous oxide (N_2O), etc.
4. Convention of Biological Diversity—the majority of nations who participated the UNCED signed in 1992 to ensure the sustainable growth of the ecosystem.
5. Agenda 21—the majority of nations who participated the UNCED signed in 1992 to establish the global consensus overcoming the environmental impacts and reaching the overall sustainable development.
6. ISO 14000—developed by the International Organization for Standardization (ISO) in 1993 and declared after three years. The generic standards provide business management with a structure for managing environmental impacts. The standards comprise a broad range of environmental disciplines, including basic environmental management system, environmental performance evaluation, auditing, labeling, life-cycle assessment, and environmental aspects in product standards.

Appendix 2

According to Shafer (1976), the mathematical theory of evidence is based on complementary *belief* and *plausibility measures.* This was motivated by previous work on upper and lower probabilities by Dempster (1967).

1. Given a universal set *X*, assumed here to be finite, a *belief measure* is a function

$$\mathrm{Bel}: P(X) \rightarrow [0, 1] \text{ such that } \mathrm{Bel}(\varnothing) = 0,\ \mathrm{Bel}(X) = 1, \text{ and}$$

$$\mathrm{Bel}(A_1 \cup A_2 \cup \cdots \cup A_n) \geq \sum_j \mathrm{Bel}(A_j) - \sum_{j<k} \mathrm{Bel}(A_j \cap A_k) + \cdots + (-1)^{n+1}\mathrm{Bel}(A_1 \cap A_2 \cap \cdots \cap A_n) \quad (2.1)$$

2. Given a universal set X, assumed here to be finite, a *plausibility measure* is a function

$$\mathrm{Pl}: \mathrm{P}(X) \rightarrow [0, 1] \quad \text{such that } \mathrm{Pl}(\emptyset) = 0, \mathrm{Pl}(X) = 1, \text{ and}$$

$$\mathrm{Pl}(A_1 \cap A_2 \cap \cdots \cap A_n) \le \sum_j \mathrm{Pl}(A_j) - \sum_{j<k} \mathrm{Pl}(A_j \cup A_k) + \cdots + (-1)^{n+1}\mathrm{Pl}(A_1 \cup A_2 \cup \cdots \cup A_n) \quad (2.2)$$

3. Let $A_1 = A$ and $A_2 = \bar{A}$ for $n = 2$, where $\bar{A}$ is the complementary set of A, then the following properties of *belief measure* and *plausibility measure* are satisfied.

$$\mathrm{Bel}(A) + \mathrm{Bel}(\bar{A}) \le 1 \quad (2.3)$$

$$\mathrm{Pl}(A) + \mathrm{Pl}(\bar{A}) \ge 1 \quad (2.4)$$

$$\mathrm{Pl}(A) = 1 - \mathrm{Bel}(\bar{A}) \quad (2.5)$$

$$\mathrm{Bel}(A) = 1 - \mathrm{Pl}(\bar{A}) \quad (2.6)$$

4. Belief and plausibility measures can conveniently be characterized by a function m: $P(X) \rightarrow [0,1]$ such that $m(\emptyset) = 0$ and $\sum_{A \in P(X)} m(A) = 1$. This function is called a basic probability assignment.
5. Let a given finite body of evidence $\langle \Im, m \rangle$ be nested. Then the associated belief and plausibility measures have the following properties for all $A, B \in P(X)$:

$$\mathrm{Bel}(A \cap B) = \min[\mathrm{Bel}(A), \mathrm{Bel}(B)] \quad (2.7)$$

$$\mathrm{Pl}(A \cup B) = \max[\mathrm{Pl}(A), \mathrm{Pl}(B)] \quad (2.8)$$

6. Let *necessity measures* and *possibility measures* be denoted by the symbols Nec(·) and Pos(·), respectively. Those measures are a special branch of evidence theory that deals only with bodies of evidence whose focal elements are nested. Therefore, we have following basic equations of possibility theory, which hold for every $A, B \in P(X)$

$$\mathrm{Nec}(A \cap B) = \min[\mathrm{Nec}(A), \mathrm{Nec}(B)] \quad (2.9)$$

$$\mathrm{Pos}(A \cup B) = \max[\mathrm{Pos}(A), \mathrm{Pos}(B)] \quad (2.10)$$

7. Since necessity measures are special belief measures and possibility measures are special plausibility measures, hence the following properties hold:

$$\text{(a)} \begin{cases} \mathrm{Nec}(A) + \mathrm{Nec}(\bar{A} \le 1 \\ \mathrm{Pos}(A) + \mathrm{Pos}(\bar{A}) \ge 1 \\ \mathrm{Nec}(A) = 1 - \mathrm{Pos}(\bar{A}) \end{cases} \quad (2.11)$$

$$\text{(b)} \begin{cases} \min[\mathrm{Nec}(A), \mathrm{Nec}(\bar{A})] = 0 \\ \max[\mathrm{Pos}(A), \mathrm{Pos}(\bar{A})] = 1 \end{cases} \quad (2.12)$$

$$\text{(c)} \begin{cases} \mathrm{Nec}(A) > 0 \Rightarrow \mathrm{Pos}(A) = 1 \\ \mathrm{Pos}(A) < 1 \Rightarrow \mathrm{Nec}(A) = 0 \end{cases} \quad (2.13)$$

On the other hand, the concept of a fuzzy measure was introduced by Sugeno (1974). Fuzzy measures are used to assign a value to each crisp subset of the universal set to represent the degree of evidence that a particular element belongs to the set. The fuzzy measure g must satisfy three axioms as in definition 1 in the section "Ranking the fuzzy measure and aggregation," in the main text, that is boundry conditions, monotonicity, and continuity.

If a fuzzy measure $g(\cdot)$ satisfies the additive condition $g(A \cup B) = g(A) \cup g(B)$, for $A \cap B = \emptyset$, then $g(\cdot)$ is a *probability measure.* It can be seen that the probability measure is one of fuzzy measures with additivity.

It follows from the above monotonicity that

$$\begin{cases} g(A \cup B) \ge \max\{g(A), g(B)\} \\ g(A \cap B) \le \min\{g(A), g(B)\} \end{cases} \quad (2.14)$$

In the strict cases, we have

$$\begin{cases} g(A \cup B) = \max\{g(A), g(B)\} \\ g(A \cap B) = \min\{g(A), g(B)\} \end{cases} \quad (2.15)$$

The former is called the *possibility measures* Pos(·), and the later is called the *necessity measure* Nec(·), those have same meaning and properties as above evidence theory.

Furthermore, the relationship among the six types of measures employed can be depicted in Figure 3.

Appendix 3

In this article we utilize nonadditive Choquet integrals to aggregate fuzzy performance scores with weights. Here we give an example to compare the results with traditional independent assumption among considered criteria.

Example

Consider an employer who would like to recruit new staff for the company. The recruiting committee set three criteria, skill (C1), professional knowledge (C2) and experience (C3). Three persons, A, B, and C, are interviewed, and the scores from interviewers are summed as follows:

Recruit	Skill (C_1)	Knowledge (C_2)	Experience (C_3)
A	90	80	50
B	50	60	90
C	70	75	70

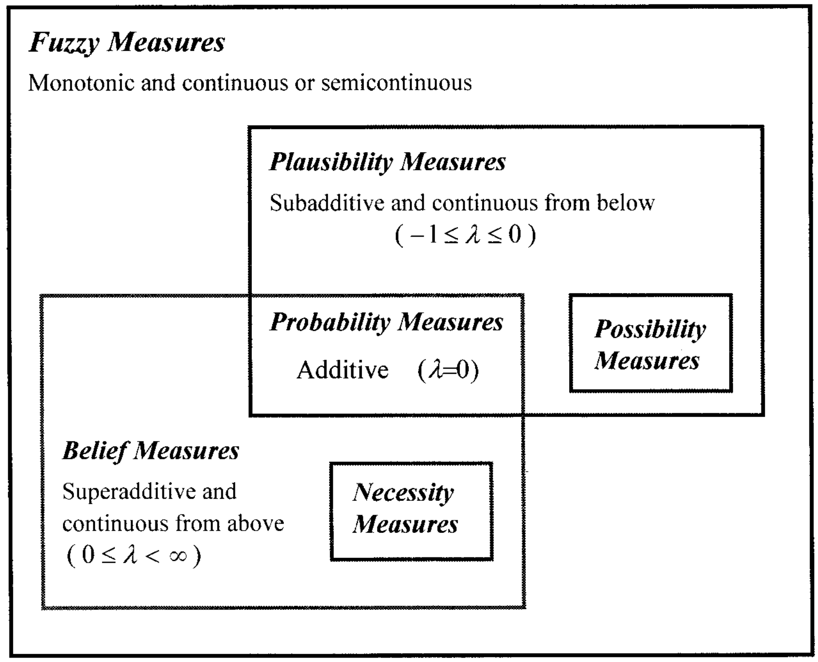


Figure 3. Relationship among the types of measures discussed.

In addition, the committee set the weights as follows:

$$\mu(\{c_1\}) = \mu(\{c_2\}) = 0.45; \quad \mu(\{c_3\}) = 0.3; \quad \mu(\{c_1, c_2\}) = 0.5; \quad \mu(\{c_2, c_3\}) = \mu(\{c_1, c_3\}) = 0.9,$$

Applying the Choquet integral with the above fuzzy measure and the traditional weighted mean methods leads to following evaluation:

Recruit	Global evaluation (Choquet integral)	Global evaluation (weighted mean)
A	69.50[a]	76.25[b]
B	68.00	63.75
C	72.25	71.875

a. Nonindependent case among criteria: where g(·) presents fuzzy measure of criteria, and C_1, C_2, and C_3 are defined as above.

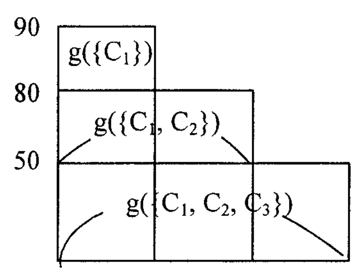
b. Independent case among criteria:

1. Find the criteria weights through normalization:

$$g(\{C_1\}) = g(\{C_2\}) = 0.375; \quad g(\{C_3\}) = 0.25$$

2. Global evaluation = 90 * 0.375 + 80 * 0.375 + 50 * 0.25 = 76.25

Through the above results, we can see the difference between independent and nonindependent cases based on ranking by global evaluation. If the criteria considered have nonindependent relationships (either substitutive or multiplicative), fuzzy integrals might be an appropriate method to evaluation.



g({C1}) = 0.45; g({C1, C2}) = 0.50g({C1, C2, C3}) = 1.0
Global evaluation
= (90−80) * 0.45 + (80 − 50) * 0.5 + * 1.0 = 69.50

Appendix 4

How to conduct the final synthetic utilities is a concern for analysts. Here we summarize the procedure of nonadditive fuzzy hierarchical analytic approach as follows.

1. Setting up the hierarchical system including goals, subobjectives, criteria, alternatives/strategies.
2. Generating the relative important score of considered criteria and performance score (called h_{ij} with the ith strategy corresponding to the jth criterion in this article) of alternatives by subjective judgment of evaluators. Utilizing statistical factor analysis to extract independent common factors from criteria scores will help the analyst to verify independent or nonindependent relationships among criteria.
3. Establishing pairwise comparison matrix among criteria and then aggregating the relative weights (called w_j for the jth criterion in this article) using a geometric mean or other appropriate method.
4. Using the fuzzy integral technique to aggregate performance score with weights in common factors, the evaluation value called u_i corresponding to the ith strategy in this article. Then employing the weighted mean method to gain the final synthetic utilities of each alternative. There exist independent relationships among common factors.
5. Ranking the alternatives based on their final synthetic utilities will provide useful information to decision-maker.

Example

Consider one decision-making case including three independent criteria, C_1, C_2, C_3, and four alternatives, A_1, A_2, A_3, A_4. In addition, define h_{ij} to represent the performance score with the ith alternative corresponding to the jth criteria, (a higher performance score is better), and w_j to represent the weight with respect to the j th criteria. If we have an ordinary performance matrix $\boldsymbol{H} = [h_{ij}]$, and have driven the ordinary weights $\mathbf{w} = [w_j]^T$ as follows,

$$\mathbf{H} = \begin{bmatrix} 5 & 1 & 9 \\ 7 & 3 & 5 \\ 3 & 7 & 1 \\ 5 & 7 & 9 \end{bmatrix} \qquad \mathbf{w} = \begin{bmatrix} \frac{1}{3} & \frac{1}{5} & \frac{7}{15} \end{bmatrix}^T$$

Moreover, we define $u_i = \sum_j h_{ij} \cdot w_j$ as representing the final utility corresponding to the ith alternative. Then we conduct the final utilities as $\mathbf{u} = [6.067\ 5.267\ 2.867\ 7.267]^T$. Finally, the ranking of alternatives based on final utilities as $A_4 > A_1 > A_2 > A_3$, where $A > B$ means A is preferential to B.

On the other hand, if we define a triangular fuzzy number as in an earlier section:

$$\tilde{1} = (1, 1, 3); \quad \tilde{3} = (1, 3, 5); \quad \tilde{5} = (3, 5, 7); \quad \tilde{7} = (5, 7, 9); \quad \tilde{9} = (7, 9, 9)$$

then we can transfer the ordinary performance score matrix and ordinary weighting to fuzzy performance matrix $\tilde{\boldsymbol{H}} = [\tilde{h}_{ij}]$ and fuzzy weights $\tilde{\boldsymbol{w}} = [\tilde{w}_j]^T$ as in the following matrix:

$$\tilde{\mathbf{H}} = \begin{bmatrix} 3 & 5 & 7 & 1 & 1 & 3 & 7 & 9 & 9 \\ 5 & 7 & 9 & 1 & 3 & 5 & 3 & 5 & 7 \\ 1 & 3 & 5 & 5 & 7 & 9 & 1 & 1 & 3 \\ 3 & 5 & 7 & 5 & 7 & 9 & 7 & 9 & 9 \end{bmatrix}$$

$$\tilde{\mathbf{w}} = \begin{bmatrix} \frac{3}{15} & \frac{5}{15} & \frac{7}{15} & \frac{1}{15} & \frac{3}{15} & \frac{5}{15} & \frac{5}{15} & \frac{7}{15} & \frac{9}{15} \end{bmatrix}^T$$

where we define the fuzzy final utility as $\tilde{u}_i = (\tilde{h}_{i1} \otimes \tilde{w}_1 \oplus \tilde{h}_{i2} \otimes \tilde{w}_2 \oplus \tilde{h}_{i3} \otimes \tilde{w}_3)$, where $\oplus$ and $\otimes$ are addition and multiplication operators in fuzzy number arithmetic. Then we can intuitively compute the fuzzy final utility $\tilde{\mathbf{u}} = [\tilde{u}_i]$ as follows.

$$\tilde{\mathbf{u}} = \begin{pmatrix} 3.000 & 6.067 & 9.667 \\ 2.067 & 5.267 & 10.07 \\ 0.867 & 2.867 & 7.133 \\ 3.267 & 7.267 & 11.67 \end{pmatrix}$$

Furthermore, utilizing the center-of-area method to conduct the best nonfuzzy performance value of final utility as $\mathbf{u} = (6.244\ 5.800\ 3.622\ 7.400)^T$, the ranking of alternatives based on final utilities as $A_4 > A_1 > A_2 > A_3$, we have the same ranking result as in the case of crisp ordinary weights. It is important that fuzzy measure and fuzzy synthetic appraisal might be appropriately used to evaluate the subjective semantic judgments or qualitative methods used in evaluating process for social science research such as in public policy, mass transit system, environmental issues.

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