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Using Fuzzy Delphi Method in Maintenance Strategy Selection Problem

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Abstract

In this paper, a new approach that applies fuzzy Delphi method in Simple Additive Weighting (SAW) is proposed to be used in the Maintenance Strategy Selection Problem (MSSP). This approach is based on representation of the importance of goals and each strategy capabilities to satisfy each maintenance goals with fuzzy numbers. Fuzzy Delphi method is applied for the assessment of the importance of each goal and capability of each maintenance strategy, considering the expert's opinion. This method considers both tangible and intangible goals dealing with the selection problem. Fuzzy Delphi method generates an L-R fuzzy number that measures information about the nature of opinions more adequately. Yager ranking method is used in transforming fuzzy numbers in the selection problem. Finally, through a heuristic algorithm, the main steps of the proposed method are presented.

Keywords: maintenance, maintenance strategy selection problem, fuzzy Delphi method, fuzzy numbers, SAW method

1 Introduction and Literature Review

Maintenance costs constitute a major part of total operating costs of all manufacturing and production plants [16]. The selection of inefficient maintenance strategy has consequences on direct maintenance costs in an organization. Selection of most efficient maintenance strategy is an important problem that an organization is dealing with. A proper maintenance strategy, applied to equipment will save money for the organization. Many of the goals dealing with the selection of the best maintenance strategy for equipment in an organization are non-monetary or intangible, which beside the monetary goals makes the selection problem more complex.

In the literature, there are few studies that have been done on the MSSP. Murthy and Asgharizade [2] proposed an approach for decision making when the company out sources the maintenance. They used game theory to conduct a decision when the customer (the receptionist of maintenance) wants to decide whether having a service contract or not. Bertolini and Bevilacqua [3] used a combined AHP-GP model for maintenance selection policy problem and in a case study used it for identifying the optimal maintenance policy for a set of centrifugal pumps operating in the process and service plants of an Italian oil refinery. Al-Najjar and Alsyouf [4] consider the most efficient maintenance approach as the one that is able to provide and utilize the required information about the changes in the failure causes behavior. They used past data and technical analysis of processes machines and components to identify the criteria for an MCDM problem. They used fuzzy Inference System (FIS) to assess the capability of each maintenance approach. Finally utilizing SAW, the efficient maintenance approach was selected. Löfsten [20] proposed a model based on cost analysis to choose between corrective or preventive maintenance. Sharma [21] proposed an approach based on fuzzy linguistic modeling to select the most effective maintenance strategy for the components/parts associated with the system. Luce [22] proposed a method to select the most economical maintenance method by utilizing Weibull law in

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order to represent reliability and evaluate maintenance costs. Bevilacqua and Barglia [7] used AHP coupled with a sensitivity analysis for maintenance strategy selection in an Italian Oil refinery. Triantaphyllou *et al*. [8] proposed a method to find the criticality of each criteria dealing with maintenance strategies in which deals with the simplifying of the complex maintenance criteria. Almedia and Bohoris [9] present a review of some basic decision theory concepts and discussed their applicability in the selection of maintenance strategies. Ivy and Nembhard [13] integrate statistical quality control (SQC) and partially observable Markov decision processes (POMDPs) for the evaluation of maintenance policies under conditions of limited information.

One of the crucial steps in many decision making process is accurate estimation of pertinent data relevant to the problem. The MSSP which is a multi criteria decision making (MCDM) problem faces the problem in estimating the related factors. To solve this problem, some approaches using fuzzy concepts have been proposed. Wang *et al*. [5] used fuzzy AHP for the evaluation of maintenance strategies. They used triangular fuzzy number (TFN) in fuzzy AHP to model the uncertainty in the selection process. Mechaefske [6] used a fuzzy linguistic approach for the MSSP. In his approach, the organization firstly select its goals then by interviewing the managers and employs the importance of each goal and the capability of each maintenance strategy to satisfy each goal is captured, then by utilizing some equations in the fuzzy environment the optimum maintenance strategy will be selected. The problem of his approach is that he did not consider the variety of opinions and limit the opinions to deterministic linguistic variables.

It is obvious that an efficient selection process must have the ability of determining the best maintenance strategy under any uncertainty level. The variety of maintenance criteria and their importance in an organization have many effects on the selection process and it makes the problem complex to deal with all of the variety in the selection process. In this paper, a new approach to the MSSP is proposed which can determine the best maintenance strategy by considering the uncertainty level and also all the variety in maintenance criteria and their importance. Fuzzy Delphi method is used in SAW shown in a heuristic algorithm for the estimation of the importance of goals and the capability of each maintenance strategy to satisfy each maintenance goal. This approach can consider all of the goals (tangible or intangible) dealing with the selection of maintenance strategies in an organization. Consider that fuzzy Delphi method generates L-R fuzzy numbers, which can measure more adequate information about the nature of opinions. SAW as a best known and very widely used method of Multiple Attribute Decision Making (MADM) is used in this paper in order to conduct the decision.

This paper is organized as follows: Section 2 reviews some popular maintenance strategies and represents some factors in which an organization maybe consider for the selection of its maintenance strategy. Section 3 presents the proposed method. Finally, through a heuristic algorithm in section 4, the main steps of the proposed method are presented.

2 Maintenance Strategies and Maintenance Goals

2.1 Alternative Maintenance Strategies

In the following, three alternative maintenance strategies are considered in this paper and also a review of maintenance goals divided into two different aspects (tangible and intangible) are presented.

In the literature there are several categorizations of maintenance strategies (e.g. Wang *et al.* [5]; Mechaefske [6]; Bertolini and Bevilacqua [3]) based on their goals in decision making or identification. In this paper we considered only three maintenance strategies for illustrating the proposed selection method. Note that the proposed approach has the flexibility to consider as many strategies as the organization wanted to insert in the selection process.

Failure based maintenance (FBM) is the original maintenance strategy which indicate that an equipment would be repaired each time it breaks down and no action is performed to detect or prevent the failure. In this case, the maintenance costs are usually high but sometimes it is cost effective [10].

To reduce frequent and sudden failures, preventive maintenance (PM) is applied, regardless of the condition of the equipment. This strategy is based on periodically planned actions performed on the equipment intended to prevent unscheduled downtime and premature equipment damage; see Mann *et al.* [11], Al-Najjar [10] and Mobley [17]. Preventive maintenance is a widely used strategy and also called time based preventive maintenance [5].

Condition based maintenance (CBM) is based on using critical components to predict failure of the equipment. The maintenance is carried out just before the failure occurs. The maintenance decision is made using measured data which is generated from monitoring systems such as vibration monitoring, lubricating analysis, and ultrasonic testing [10]. CBM is usually used for rotating and reciprocating machines in example centrifugal pumps, turbines and compressors.

Note that each organization has its own strategies based on the equipment used, therefore it is expected that an organization perform some specific maintenance strategies. In this approach, we use three alternative maintenance strategies but it should be considered that the approach is flexible and we can add any specified maintenance strategies to the selection process.

2.2 Factors Dealing with the Selection of the Maintenance Strategies

When an organization wanted to select the best maintenance strategy for equipment, firstly, its maintenance goals which are taken for comparing criteria must be set. Wang *et al.* [5] divided the maintenance goals into four aspects: (1) safety (personnel, facilities, and environment); (2) cost (hardware, software, personnel training); (3) added-value (spare parts inventories, production loss, and fault identification); (4) feasibility (acceptance by labors, technique reliability). Maintenance goals can also be considered in two different aspects: (1) tangible (2) intangible. Tangible goals are measurable and can be estimated using different tools i.e. low maintenance cost, improved reliability. Intangible goals are not measurable but can be estimated using expert tools i.e. acceptance by labors, enhance competitiveness. Note that we can measure some intangible factors using special indicators. This approach has the ability to find the most efficient maintenance strategy considering all of the factors at the same time without consideration of their tangible or intangible characteristic.

Different organizations have different maintenance goals, therefore, in this approach; it is offered to specify the maintenance goals by interviewing the maintenance staff and managers.

3 Proposed Method

The organization firstly specifies the alternative strategies which are chosen to be performed on the equipment and then by interviewing the maintenance staff and managers, the maintenance goals will be defined. Then by applying Fuzzy Delphi method the importance of each goal and the capability of each maintenance strategy to satisfy each goal will be determined. Using Yager ranking method the fuzzy numbers associated with the importance of each goal and the capability of each maintenance strategy to satisfy each goal will be transformed to crisp values and finally by specializing SAW as probably best known and very widely used method of MADM, the best maintenance strategy will be selected.

Different tools used in order to determine the best maintenance strategy are described as follows.

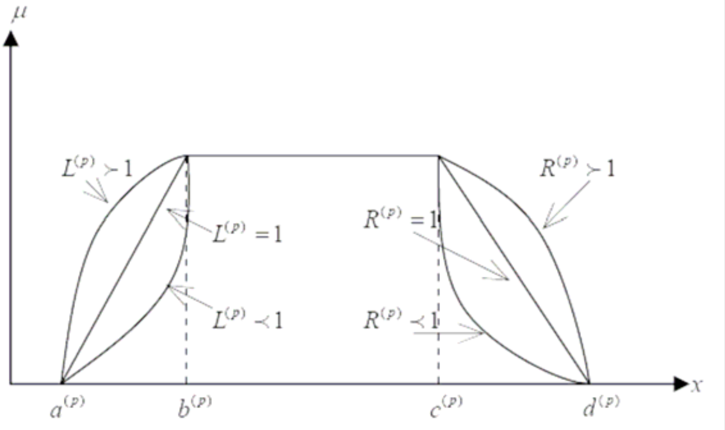
3.1 Fuzzy Delphi Method

The Delphi method is an iterative process to collect and distill the anonymous judgments of experts. Fuzzy Delphi method uses a serious of data collection and analysis techniques interspersed with feedback. The Delphi method is well suited as a research instrument when there is incomplete knowledge about a problem.

Fuzzy Delphi method which was proposed by Chang *et al.*[12] is employed in this paper. Chang *et al.* [12] used fuzzy statistics and the technique of conjugate gradient search to derive membership function of L-R fuzzy number (Fig.1) for the fuzzy forecasts. The procedure of Fuzzy Delphi method is illustrated in Appendix. The category of shapes of membership function derived in this paper is as follows (consider that $d^{(p)} \leq 1$):

$$\mu^{(p)}(x) = \begin{cases} 1-((b^{(p)}-x)/(b^{(p)}-a^{(p)}))^{L^{(p)}} & ,a^{(p)} \leq x \leq b^{(p)} \\ 1 & ,b^{(p)} \leq x \leq c^{(p)} \\ 1-((x-c^{(p)})/(d^{(p)}-c^{(p)}))^{R^{(p)}} & ,c^{(p)} \leq x \leq d^{(p)} \\ 0 & ,otherwise, \end{cases} \quad (1)$$

where *P* is the *Pth* survive question.



Figurer 1: Membership function of L-R fuzzy number

The survive questions in the MSSP are the importance of each goal ($\mu_j^I(x)$) and the capability of each maintenance strategy to satisfy each goal ($\mu_j^{Ci}(x)$).

After finding the membership function of the importance of *jth* goal ($\mu_j^I(x)$) and also the membership function of the capability of *ith* maintenance strategy to satisfy *jth* goal ($\mu_j^{Ci}(x)$), an approach based on a fuzzy transformation methods will be used for the selection of the best maintenance strategy.

3.2 Yager Ranking Index

Yager [14] proposed a procedure for ordering fuzzy sets based on the concept of area compensation. Area compensation possesses the properties of linearity. A ranking Index $I(\tilde{p})$ is calculated for the convex fuzzy number $\tilde{p}$ from its α-cut $\alpha_{\tilde{p}} = [P_\alpha^L, P_\alpha^U]$ according to the following formula:

$$I(\tilde{p}) = \int_0^1 \frac{1}{2}(p_\alpha^L + p_\alpha^U)d\alpha \quad (2)$$

which is the center of the mean value of $\tilde{p}$. Consider two fuzzy number $\tilde{p}_1$ and $\tilde{p}_2$, the equation $I(\widetilde{p_1}) \geq I(\widetilde{p_2})$ implies that $\widetilde{p_1} \geq \widetilde{p_2}$ [14,15]. This index is very simple to apply.

Yager ranking index is used as a transformation method for the membership function of the importance of *jth* goal ($\mu_j^I(x)$) and also the membership function of the capability of *ith* maintenance strategy to satisfy *jth* goal ($\mu_j^{Ci}(x)$).

The ranking index of $\mu_j^I(x)$ and $\mu_j^{C_i}(x)$ will be denoted as $I(\widetilde{G}_j)$ and $I(\widetilde{C}_j^i)$, respectively.

$$I(\widetilde{G}_j) = \int_0^1 \frac{1}{2}((\widetilde{G}_j)_\alpha^L + (\widetilde{G}_j)_\alpha^U)d\alpha \quad , for \quad j = 1,...,m. \tag{3}$$

$$I(\widetilde{C}_j^i) = \int_0^1 \frac{1}{2}((\widetilde{C}_j^i)_\alpha^L + (\widetilde{C}_j^i)_\alpha^U)d\alpha \quad , for \quad i = 1,...,n \quad and \quad j = 1,...,m. \tag{4}$$

3.3 Simple Additive Weighting

In order to make decisions in the presence of multiple and conflicting criteria Multiple Attribute Decision Making (MADM) is applied. In MADM, The alternatives have associated with them a level of the capability in satisfying the attributes based on which the final decision is to be made. The final decision is conducted with the help of inter and intra-attribute comparisons (see [18], [19]).

SAW is probably the best known and very widely used method of MADM. To each of the attributes in SAW, the decision maker assigns importance weights which become the coefficients of the variables. The decision maker can then obtain a total score for each alternative simply by multiplying the scale rating for each attribute value by the importance weight assigned to the attribute and then summing these products over all attributes.

SAW method can be stated as follows. Note that the formula in SAW is rearranged to become proper to proposed approach. Suppose the importance of each goal ($\mu_j^I(x)$) are assigned a set of importance weights to the goals, $\mu^I(x)$ = { $\mu_1^I(x)$, $\mu_2^I(x)$, ... $\mu_n^I(x)$ } and the capability of each maintenance strategy to satisfy each goal $\mu_j^{Ci}(x)$ are also defined through utilizing fuzzy Delphi method. Then the most efficient maintenance strategy S* is selected such that

$$S^* = \{S_i \mid \max_i \sum_{j=1}^{n} \mu_j^{C_i}(x) \times \mu_j^I(x) / \sum_{j=1}^{n} \mu_j^I(x)\} \tag{5}$$

4 Hypothetical Example

4.1 Conceptual Model of Proposed Method

As shown in Fig.2, the suggested approach consists of five main steps:

(1) Assessment of the importance of each goal using fuzzy Delphi method

(2) Assessment of the capability of each maintenance strategy to satisfy each maintenance goal using fuzzy Delphi method

(3) Defuzzifying of the L-R fuzzy numbers $\widetilde{G}_j$ and $\widetilde{C}_j^i$ using transformation methods

(4) Rank ordering the maintenance strategies using SAW method

(5) Selecting the most efficient maintenance strategy

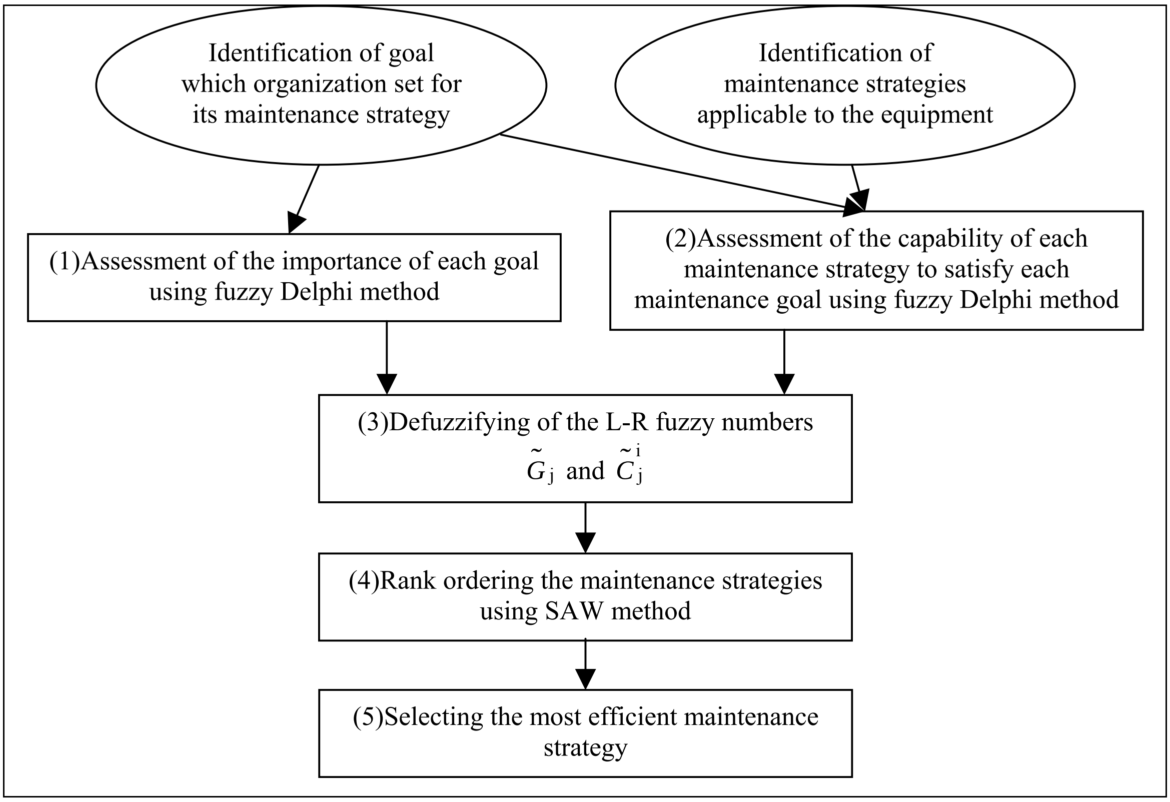


Figure 2: Conceptual model of the proposed approach

4.2 Heuristic Algorithm

A heuristic algorithm is presented based on the proposed approach for the selection of best maintenance strategy to be performed on specific equipment. It is assumed that the availability of each maintenance strategy is constant. The algorithm is presented in five steps:

Step 1: Organization specifies maintenance strategies wanted to apply to the equipment and the maintenance goals for its maintenance strategy. Consider that the goals are based on the factors in which is important to the organization. These goals maybe some or all of the following:

(1) Low maintenance cost (Tangible [6,7,5,13])
(2) Acceptance by labors (Intangible [6,5])
(3) Improved reliability (Tangible [6,1,5])
(4) Enhance Competitiveness (Intangible [6])
(5) High product quality(Tangible [6,7])
(6) Minimum inventories(Tangible [6,7,5])

The strategies that the organization selected are:

(1) Failure based maintenance (FBM)
(2) Preventive maintenance (PM)
(3) Condition based maintenance (CBM)

Step 2: Using fuzzy Delphi method by interviewing managers and employees of the maintenance department of the organization as experts, the membership function of the importance of *jth* goal ($\mu_j^I(x)$) is derived (Table 1).

Table 1: Fuzzy weight of the importance of each goal

Goal	Importance					
	L	**R**	**a**	**b**	**c**	**d**
Low maintenance cost	2.3	4.5	0.6	0.8	0.8	0.1
Feasibility (acceptance by labors)	5.3	2.1	0.3	0.4	0.4	0.5
Improved reliability	4.1	5.7	0.4	0.5	0.5	0.8
Low downtime length	1.2	4.3	0.6	0.74	0.74	0.91
Improved safety	2.5	4.1	0.3	0.71	0.71	0.8
High product quality	6.2	8.1	0.6	0.89	0.89	0.94
Minimum inventories	1.4	1.7	0.3	0.4	0.4	0.49

Note that the universe of discourse was $U = [0,1]$ in which one is the highest degree of importance.

Step 3: Using fuzzy Delphi method, the membership function of the capability of *ith* maintenance strategy to satisfy *jth* goal ($\mu_j^{ci}(x)$) is derived (Table 2).

Table 2: Fuzzy weight of the capability of each maintenance strategy to satisfy each goal

Goal	**Strategy**																	
	FBM						**PM**						**CBM**					
	L	**R**	**A**	**b**	**c**	**d**	**L**	**R**	**A**	**b**	**c**	**d**	**L**	**R**	**A**	**b**	**c**	**d**
1	5.5	4.6	0.3	0.4	0.4	0.5	6.8	9.5	0.5	0.8	0.8	0.94	2.7	6.8	0.4	0.6	0.6	0.7
2	3.1	4.5	0.5	0.7	0.7	0.8	9.7	7.1	0.4	0.6	0.6	0.7	1.9	6.1	0.4	0.5	0.5	0.9
3	6.8	3.7	0.3	0.6	0.6	0.7	2.6	0.8	0.4	0.5	0.5	0.9	2.8	9.7	0.5	0.6	0.6	0.7
4	3.6	2.5	0.2	0.4	0.4	0.5	7.2	8.8	0.5	0.7	0.7	0.9	1.3	0.7	0.5	0.6	0.6	0.68
5	5.8	6.2	0.4	0.6	0.6	0.7	0.6	0.7	0.71	0.8	0.8	0.91	9.1	5.5	0.5	0.7	0.7	0.9
6	7.3	7.1	0.4	0.6	0.6	0.7	8.9	1.3	0.7	0.8	0.8	0.84	6.9	2.5	0.5	0.6	0.6	0.8
7	8.6	5	0.3	0.4	0.4	0.6	0.1	7.5	0.53	0.6	0.6	0.8	0.5	1.6	0.3	0.5	0.5	0.7

Step 4: Utilizing Yager ranking method, the membership functions defuzzified to crisp numbers. Crisp values of membership functions of importance of each goal and the capability of each strategy to satisfy each maintenance goal are illustrated in Tables 3 and 4.

A MATLAB ® is used to solve the algorithms of Yager ranking index of membership functions.

Step 5: Based on the SAW method, the values of S_1, S_2 and S_3 for PM, CBM, and FBM, respectively, are calculated and shown in Table 5. Based on the measured values, the maintenance strategies ranked and the best maintenance strategy will be selected.

Table 3: Crisp values of the importance of each goal using Yager ranking method

Goal	Importance
	Yager ranking method
Low maintenance cost	0.7879
Feasibility (acceptance by labors)	0.4082
Improved reliability	0.5126
Low downtime length	0.7242
Improved safety	0.7397
High product quality	0.8726
Minimum inventories	0.4144

Table 4: Crisp values of the capability of maintenance strategies using Yager ranking method

	Strategy		
Goal	FBM	PM	CBM
1	0.4012	0.7874	0.5794
2	0.6938	0.5968	0.5109
3	0.6020	0.5972	0.5915
4	0.3925	0.6980	0.6018
5	0.5922	0.8042	0.7055
6	0.5938	0.8254	0.6222
7	0.4115	0.7742	0.5718

Table 5: Final results

Maintenance strategy	S_i
Preventive maintenance (PM)	0.742569
Condition based maintenance (CBM)	0.606743
Failure based maintenance (FBM)	0.519974

4.3 Result Discussion

The value of S_i declares the strategy's tendency to capture the goals therefore each strategy which has the highest S_i value has the most power to capture the goals which the organization defined. Preventive maintenance is selected as the best maintenance strategy in this case because of its highest preference value.
Note that to use fuzzy Delphi method, the maintenance staff and managers should participate because the more the participants are aware of the problem, the more accurate the result would be.

5 Conclusion

The MSSP must be considered as an important management problem because of its effective roles in production and manufacturing. The accuracy in the selection of efficient maintenance strategy for an equipment is based on determining the right maintenance goals in the decision making process. The main problem in decision making process is that there are some goals which are intangible. To deal with the right decision in the selection of best maintenance strategy, in this paper, fuzzy Delphi method is applied. Yager ranking method is employed to transfer the result of fuzzy Delphi method to crisp values. Hopefully, this approach can assist decision makers in the selection of the most efficient maintenance strategy. Further research can be focused on applying fuzzy Delphi method to AHP to measure the intangible criteria dealing with the selection of best maintenance strategy.

Appendix: Fuzzy Delphi Method Used in this Paper [12]

***Step* 1:** Set the iteration counter *k* equal to one.

***Step* 2:** A group of n experts is desired to give an interval-valued opinion [$q_k^{(i)}, r_k^{(i)}$] on each survey where *i* is the *i*th expert and p is the *p*th survey question.

***Step* 3:** For each survey item *p* compute a discrete membership function:

(1) Let $U = [0,1]$ be the universe of discourse. Partition U into S contiguous interval: $I_1, I_2, ..., I_s$ .For each I_s let x_s denotes the midrange of I_s to represent I_s .

(2) Calculate $y_s^{(p)}$ as follow:

$$y_s^{(p)} = \sum_{i=1}^{n} \delta_s^{(i,p)}, \tag{A1}$$

where

$$\delta_s^{(i,p)} = \begin{cases} 1 & if \;\; xs \in [q_k^{(i)}, r_k^{(i)}]^{(p)} \\ 0 & otherwise. \end{cases} \tag{A2}$$

(3) The discrete membership function for survey *p* then can be characterized by

$$Y^{(p)}(x_s) = \frac{y_s^{(p)}}{y_*^{(p)}}, \qquad s = 1, ..., S. \tag{A3}$$

where

$$y_*^{(p)} = \max_{s=1,...,S} \left\{ y_s^{(p)} \right\}. \tag{A4}$$

***Step* 4:** For each survey *p*, use the results obtained in Step 3 and the technique of the conjugate gradient search to obtain the continuous mathematically explicit membership function. The fuzzy opinion for the survey can be conveniently denoted as $O_k^{(p)} = (a_k^{(p)}, b_k^{(p)}, c_k^{(p)}, d_k^{(p)})$ with $a_k^{(p)} \le b_k^{(p)} \le c_k^{(p)} \le d_k^{(p)}$.

***Step* 5:** Generate the feedback information for the next iteration by using the α-level cut of fuzzy opinion $O_k^{(p)}$:

$$[O_k^{(p)}]_\alpha = \{x \mid \mu_k^{(p)}(x) \ge \alpha\} = \{l_k^{(p)}(x), u_k^{(p)}(x)\}. \tag{A5}$$

***Step* 6:** Prepare data for stability testing of fuzzy Delphi process, by using the OM index for each item *p*:

$$OM(O_k^{(p)}) = \int_{\rho^*}^{1} \varpi(w)[x_1(w) \times l_k^{(p)}(w) + x_2(w) \times u_k^{(p)}(w)]dw, \tag{A6}$$

Where $\varpi(w)$ denotes the weighting measure of the *w*-level cuts of $O_k^{(p)}$ and $x_1(w)$ and $x_2(w)$ the measures of pessimism an optimism, respectively, of $O_k^{(p)}$ under *w* and also ρ^* assumed to be greater than zero.

***Step* 7:** If all the differences of the fuzzy opinions between two consecutive iterations for each item *p* appear to be smaller than the given criterion δ , the process is complete and the final estimates are the fuzzy opinions obtained at the last iteration; Otherwise increase *k* by one and return to Step 2.

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