Multiagent Decision Making:

Personal Estimation and Group Utility

2002 International Computer Symposium (ICS2002)

Workshop on Artificial Intelligence

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Abstract. In multi-agents systems, different agents cooperate with dissimilar concepts, and each agent represents certain person who wants to achieve the most beneficial result. In several cases, some agents have to organize to be a group, and provide one decision to represent this group's whole volition, especially in Virtual Enterprise applications. In this paper, we are aimed at providing a mechanism to multi-agents decision-making procedure with no partiality of each participating agent in the group. In the first part, we use Fuzzy AHP to assist each agent to evaluate a problem. In the second step, we seek to elicit the cooperation level from each agent's inner world, and each agent will be awarded to a comparative importance according to the cooperation level. Further, the group decision can be easily made up. Finally, we propose a methodology to adapt group's preference functions. It can make all the participating agents have the chances to pick up the most favorite choice after several rounds of decision-making process.

Keywords: *Fuzzy, Analytical Hierarchy Process, Virtual Enterprise, Group Decision Making*

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1 Introduction

Group decision-making is among the most important and frequently encountered processes within companies and organizations. Individual group members will have their own motivations and, hence, will be in conflict on certain issues [3]. Nevertheless, since the group members are 'supposed' to be striving for the same goal and have more in common than in conflict, it is usually best to work as a group and attempt to achieve consensus. Therefore, group decision-making becomes a critical issue when these participants have to select a decision. Agents are often used to assist in group decision-making and problem solving [1][4]. Each agent can be said to have a different perspective on the problem.

In this paper, we attempt to use Fuzzy Analytical Hierarchy Process (Fuzzy AHP) to assist each agent to evaluate a problem in the form of a hierarchy of references through a series of pair-wise comparisons of relative criteria. A group decision mechanism consists of a process for selecting one of the alternatives based upon the preferences of the individual agents making up the group. It is clear that any nondiscriminatory decision mechanism should treat all the participants in the same way; it should not use any information about the participants other than their preferences. We shall call this condition impartiality [7]. Since Fuzzy AHP could not satisfy this criterion, we can apply the multi-agent decision procedure, which was proposed by Yager [7], to benefit from the strategic manipulation of the preference function they provide to the group decision mechanism. However, what must be kept in mind is that each of the individual agent's real objective is not the maximization of the group function but the maximization of their own individual preference function.

Nevertheless, it seems that the multi-agent decision procedure is engaged in the same decision maker in a long-term situation is unfair. Therefore, we proposed a mechanism to adapt the preference weights of each agent. This mechanism will adjust each agent's weight whenever a group decision is made.

The paper is set up as follows: the usage of Fuzzy AHP is reviewed in Section 2. In Section 3, we introduce the multi-agent decision procedure. In Section 4, a tuning weight methodology is proposed. Then we integrate these processes and have an example illustration in Section 5 and Section 6. Finally, conclusions and recommendations are presented in Section 7.

2 Fuzzy Analytical Hierarchy Process

The Fuzzy Analytic Hierarchy Process (Fuzzy AHP) is a streamlined approach to cope with decision-making. The purpose of the Fuzzy AHP is to select the best choice from a number of alternatives, which are evaluated with respect to several criteria [5][6]. In this paper, we use the Fuzzy AHP to choose the individual agent's decision from several alternatives. Therefore, individual agents will pick the best solution out, and try their best to gain the best effort.

In the first step of the Fuzzy AHP, the decision maker has to construct the hierarchy structure of a goal, which is the same with traditional AHP [5][6]. The simplest form used to structure a decision problem is consisting of three levels shown in Fig. 1. The goal of the decision is laid at the top level. The following is criterion level, which is assumed to be linear independent from one to another. The alternative is the lowest level, which will be evaluated by each criterion. Hierarchical decomposition of complex system is used by the human mind to find out the diversity from each criterion. Once the structuring is completed, the Fuzzy AHP is surprisingly simple to apply [5][6].

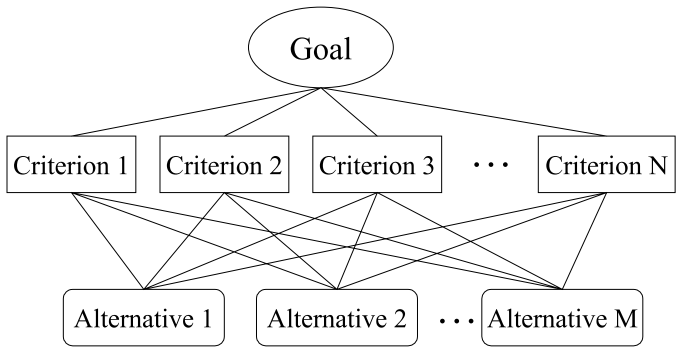

Fig. 1. A three level hierarchy

In the second step, each decision maker should subjectively accomplish the pair-wise matrices between goal and criterion layer [5][6], which is shown in Eq. (1).

$$B = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & .. & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & .. & \frac{w_2}{w_n} \\ \vdots & \vdots & & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & .. & \frac{w_n}{w_n} \end{bmatrix} = \begin{bmatrix} 1 & b_{12} & .. & b_{1n} \\ 1/b_{12} & 1 & .. & b_{2n} \\ \vdots & \vdots & & \vdots \\ 1/b_{1n} & 1/b_{2n} & .. & 1 \end{bmatrix} \quad (1)$$

where B is the pair-wise comparison matrix (size $n \times n$); $\frac{w_x}{w_y}$ represents the relative importance of the x-th criterion over the y-th criterion $(x, y \in 1,2,...,n)$. In general, the value of $\frac{w_x}{w_y}$ is given by a decision maker subjectively. There are $n(n-1)$ judgments b required to develop the set of matrices. Reciprocals are automatically assigned in each pair-wise comparison shown in Eq. (1).

Separately, we use different methodology to accomplish the assessment between criterion layer and alternative layer. For a given fuzzy set *F*, the membership function $\mu_F(x)$ is usually defined as the form $\mu_F : x \to [0,1]$ where [0,1] denotes the interval of real numbers from 0 to 1, inclusive. Then we use Center of Gravity defuzzification process to get the comparative value of each alternative. The Center of Gravity defuzzification is shown in Eq. (2).

$$a = \sum_i \frac{x_i[\mu_F(x_i)]}{\mu_F(x_i)} \quad (2)$$

where *a* is the relative value of each alternative.

In the third step, we can get the priority vector of each matrix. The hierarchical weighting method is usually used to find the priority vector of each alternative [5][6]. The priority vector of each matrix can be expressed by a set of linear equations $W_1, W_2, ..., W_n$. The summation of $W_1, W_2, ..., W_n$ is always equal to 1, which is shown in Eq. (3).

$$W_1 + W_2 + ... + W_n = 1 \quad (3)$$

The other way of synthesizing is the ideal mode. In this mode, the priority vectors of the alternatives for each criterion are divided by the value of the highest rated alternative that becomes the ideal and receives a value of 1.

Finally, we can synthesize the priorities. There are two ways of doing that. One is the distributive mode. The other way of synthesizing is the ideal mode. The alternative becomes the ideal and receives a value of 1.

3 Multi-Agent Decision Making

We use Fuzzy AHP to aware of the individual agent the preference degree of each alternative. Because the Fuzzy AHP has to give different importance of each agent when we want to make the group decision. It is clear that any nondiscriminatory decision mechanism should treat all the participants in the same way; it should not use any information about the participants other than their preferences [7].

One of the alternatives which is from set $A = \{A_1, A_2, \ldots A_m\}$ must be chosen as a group decision. Let A denote a universal set. Besides, all of the n agents must cooperate in this mechanism. Each agent will provide its preference over the set A. $Agent_i$ denotes as the agent i, then $Agent_i(A_j)$ represent how satisfied $Agent_i$ is. We assume each agent assigns a value of one to its most preferred alternatives. Meanwhile, the agent is unable to know the other participating agents' preferences.

The way we combine all the individual agents is denoted as *GAgent*, also a subset of A. As soon as we have the group preference, the mechanism will pick the largest value in *GAgent*. Generally speaking, we know that the alternative is based upon the preference information which is provided by each of the individual participating agents.

Here we formally define the collaborative imperative function h to provide varied group decision-making mechanism. The mapping of imperative function is $h: I \to I$. I is the importance of the total score, where $I \in [0,1]$. The higher importance value I means more important in the aggregation process. If r proportions of the members are satisfied with a solution, we use *h(r)* to express the group satisfaction of a solution. Besides, we know that the collaborative imperative function has numbers of properties to be related. If nobody is satisfied by a solution in the group, the group has zero satisfaction, $h(0) = 0$. Oppositely, if everybody is satisfied, the group should have completed satisfaction, $h(1) = 1$. The more individual satisfaction, the more group satisfaction, $h(x) \geq h(y)$ if $x > y$. Thus, $h: I \rightarrow I$ is a mapping such that

1) $h(0) = 0$

2) $h(1) = 1$

3) $h(x) \geq h(y)$ if $x > y$.

Fig. 2 shows two other examples of collaboration imperative. In the linear case $h(r)=r$ and in the power case $h(r)=r^2$. We note that all of these are particular cases of a whole family of collaborative imperatives, $h(r) = r^{\alpha}$ where $\alpha \in (-\infty, \infty)$.

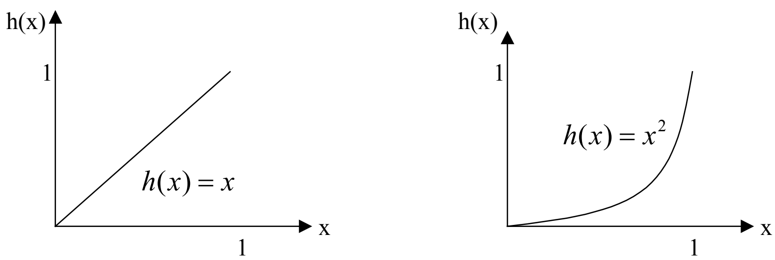

Fig. 2. Additional collaborative imperative

As already indicated, we use the individual preference to know the collaboration level of each agent and to make an agent's importance proportional to the total preferences. One way we accomplish this is described in the following. Assume we have *n* agents, each providing a preference $Agent_i(A_j)$ over the space of possible courses of action. Let $S_i = \sum_j Agent_i(A_j)$ and let $S = \sum_{i=1}^{n} S_i$. Using this, we get an importance weight for agent *i*, $I_i = \left(S_i / S \right)$. Thus, an agent's influence is made proportional to his score. Furthermore, we assume the agents have agreed to use the collaboration imperative *h*.

The first step is to calculate the aggregate importance value u_i, where $u_i = \sum_{k=1}^{i} I_k$. Then we can estimate the weight of each agent, shown in Eq (3).

$$w_k = h(u_k) - h(u_{k-1}) \tag{4}$$

After calculating the weight of each agent for a certain alternative, we then combine all of the agents' weights and satisfactions in the second step. For a given alternative A_j, we shall let $Agent_i(A_j)$ denote the score given by the ith agent and let $GAgent(A_j) = F_h(Agent_1(A_j),..., Agent_n(A_j))$ indicate the aggregations of the individual scores under h; it is the group preference function. If there are n agents in the group, we can generalize to Eq. (4).

$$\begin{aligned} GAgent(A_j) &= \sum_{k=1}^{n} w_k Agent_k(A_j) \\ &= \sum_{k=1}^{n} \left((h(u_k) - h(u_{k-1})) Agent_k(A_j) \right) \end{aligned} \tag{5}$$

4 Tuning Group Decision Weight

In a group, we cannot always obey the best solution and ignore the others alternative, especially in Virtual Enterprise [2] need to make the long-term decision. It is unfair in a group decision environment. So we need to modify all of the alternative values of each agent after making the decision procedure. Whenever the group decision choose the alternative A_i, the alternative A_i will be tuned down in the second round; vice versa. This variation will base on approving volition of each agent. The alternative A_i will probably be chosen, or the second priority will be picked in the second round. As a result, the opinion with fewer supports still could be chosen after several rounds of decision procedures.

If the approving volition has great majority, it means that the opinion of a group has few conflict. We will tune the weight slightly. If all of the agents approve the decision, the weight will not modify. Oppositely, if the approving volition owns less proportion, the weight will change substantially.

We use this kind of mechanism to adapt each agent's weight in a group, and it will make the group decision fairly in a long-term viewpoint. So, the following weight tuning method can be introduced:

Tuning down the alternative weight that is chosen by group (shown in Eq. (5)). To avoid the value lower than 0, we use the Max operation to choose the higher one.

$$A_i' = Max\left\{0,\, A_i - A_i \times C\left(1 - P/N\right)\right\} \tag{6}$$

A_i' : the new alternative value which is modified in the second round.

A_i : the alternative value provided by the agent.

C : the tuning constant which control the variation degree. $0 \le C \le 1$

P : the number of optimal decision of the agents.

N : the total number of the agents.

Tuning up the alternative weight that is not chosen by group (shown in Eq. (6)). To avoid the value higher than 1, we use the Min operation to choose the lower one. If we have *m* alternatives, it means that there are *m*-1 alternatives not be chosen. So, the up tuning profit should be shared among these *m*-1 alternatives.

$$A_i' = Min\left\{1,\, A_i + A_i \times C \times \frac{1}{m-1}\left(1 - P/N\right)\right\} \tag{7}$$

5 Multi-Agent Decision Making Algorithm

In this section, we integrate the previous methodologies into an algorithm called Multi-Agent Decision Making Algorithm. From step 1 to step 4 is the personal Fuzzy AHP decision procedure. Step 5 to step 8 is the multi-agent decision-making procedure. Finally, the step 9 is the tuning group decision weight procedure.

Algorithm 1. Multi-Agent Decision Making Algorithm

Step 1: Construct the hierarchy structure of a goal.

Step 2: Subjectively accomplish the pair-wise comparison matrices between goal and criterion layer using traditional AHP methodology.

Step 3: Using simple fuzzy technique to get the comparative value of each alternative between criterion layer and alternative layer.

Step 4: Calculate and synthesize the priority vectors of each matrix.

Step 5: Until all the participant agents accomplish the ideal alternative values.

Step 6: Summation all the alternatives of each agent S_i. Higher S_i means higher conspiracy intent. Then we use $S = \sum_{i=1}^{n} S_i$ to get the group conspiracy intent. Finally, we obtain an importance weight for agent i, $I_i = \left({S_i}/{S} \right)$.

Step 7: After selection an imperative function h, we can use this imperative function to calculate the weights of each agent using the importance value u_i, where $u_i = \sum_{k=1}^{i} I_k$.

Step 8: Using Eq. (5) to compute each alternative intent of group viewpoint and choose the best one.

Step 9: Tuning the alternatives of each agent, go to step 6.

6 Illustrative Example

The main objective of a Virtual Enterprise is to allow a number of organizations to rapidly develop a common working environment; hence managing collection of resources provided by the participating organizations toward the attainment of some common goals. Because each partner brings a strength or core competence to the consortium, the success of the project depends on all cooperating as a single unit [4].

As a result of each agent owning different considerations, they can establish various criteria in the situation of each one. Here we demonstrate one example of criterion and alternative assessment, and the others can make up in the same way. *C* means the criterion, and *A* means the alternative.

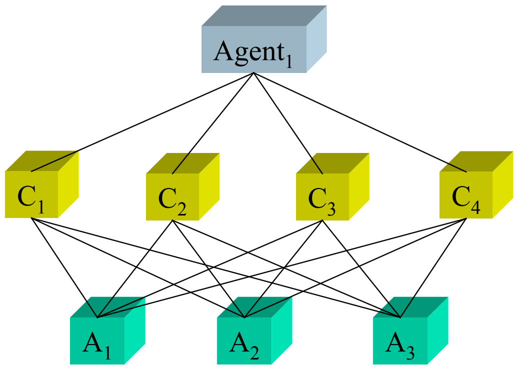

Fig. 3. The hierarchy of the agent$_1$

Fig. 3 shows the hierarchy of agent$_1$, and agent$_1$ has four criteria and three alternatives items. The agent$_1$ subjectively accomplish the criterion matrix between goal and criterion layer shown as Table 1.

Table 1. The criterion matrix using AHP

Agent$_1$	C_1	C_2	C_3	C_4	Priority Vector
C_1	1	5/4	3	3	0.4
C_2	4/5	1	4/3	3	0.3
C_3	1/3	3/4	1	7/3	0.2
C_4	1/3	1/3	3/7	1	0.1

Then we define the membership function of each criterion. Here we show the membership function $\mu_{C_1}(x)$ and the influence factor x = *{Very Low, Low, Medium, High, Very High}* with linguistic variables. In order to get the comparative importance from the crisp value, we give numerical values instead of linguistic variables. Here we define the linguistic variable 'Very Low' with a numerical value 1, and 'Very High' with a numerical value 5.

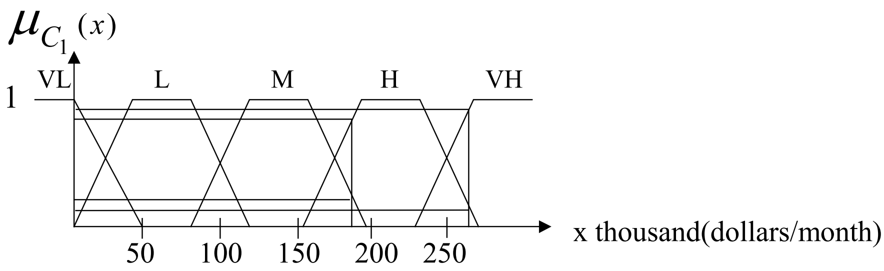

Fig. 4. Membership functions of the criterion 1 of the inputs

According to the crisp input value, we can get the corresponding membership values. In this example, there are three alternatives to be chosen with the value 180, 270, and 180 thousand (dollars/month). Fig. 4 shows that 180 thousand (dollars/month) belongs to the linguistic variables {Medium, High} with membership values of {0.8, 0.2}, respectively. We use Center of Gravity defuzzification process to get the comparative importance $(0.8\times 4+0.2\times 3)/(0.8+0.2)=3.8$. Therefore, we can easily accomplish the other two alternative A2 and A3 with the values 4.85 and 3.8. Then according the comparative importance values, we can fill in the values into the table, as shown in Table 2. In the same way, we can deal with the other matrices between criterion layer and alternative layer.

Table 2. The alternative matrix of criterion 1 using Fuzzy AHP

C_1	A_1	A_2	A_3	Priority Vector	Ideal Value
A_1	1	3.8/4.85	3.8/3.8	0.3	0.75
A_2	4.85/3.8	1	4.85/3.8	0.4	1
A_3	3.8/3.8	3.8/4.85	1	0.3	0.75

Table 3. The overall priority ranking in ideal mode with Agent$_1$

Agent$_1$	C$_1$	C$_2$	C$_3$	C$_4$
A$_1$	0.75	0.33	1	0.11
A$_2$	1	0.33	0.2	0
A$_3$	0.75	1	0.8	1

We can get the assenting level of each selective alternative with the result of Table 1 and Table 3, shown as following.

$$Agent_1(A_1) = (0.4)(0.75) + (0.3)(0.33) + (0.2)(1) + (0.1)(0.11) = 0.61$$
$$Agent_1(A_2) = (0.4)(1) + (0.3)(0.33) + (0.2)(0.2) + (0.1)(0) = 0.54$$
$$Agent_1(A_3) = (0.4)(0.75) + (0.3)(1) + (0.2)(0.8) + (0.1)(1) = 0.86$$

After completing the personal assenting level of each selective alternative, we can use the multi-agent decision procedure to make good decision in a viewpoint of a group. In this example, we assume there are four memberships in a Virtual Enterprise, and this Virtual Enterprise has to pick out one decision that is the best choice of viewing the situation as a whole. Hence, after all of the participant members accomplishing the assenting level, we can use the multi-agent decision procedure to make good decision in a viewpoint of a group. We can get their respective preferences functions are

$$Agent_1 = \left\{\frac{0.61}{A_1}, \frac{0.54}{A_2}, \frac{0.86}{A_3}\right\},\ Agent_2 = \left\{\frac{0.44}{A_1}, \frac{1}{A_2}, \frac{0.88}{A_3}\right\},$$
$$Agent_3 = \left\{\frac{0.7}{A_1}, \frac{0.5}{A_2}, \frac{0.15}{A_3}\right\},\ Agent_4 = \left\{\frac{0.7}{A_1}, \frac{0.53}{A_2}, \frac{0.53}{A_3}\right\}.$$

In this case, $S_1 = 2.01$, $S_2 = 2.32$, $S_3 = 1.35$ and $S_4 = 1.76$. Using these we get $S = 7.44$. Hence $I_1 = (2.01/7.44) = 0.27$, $I_2 = (2.32/7.44) = 0.31$, $I_3 = (1.35/7.44) = 0.18$, and $I_4 = (1.76/7.44) = 0.24$.

Assume our collaborative imperative is $h(x) = x^2$. Let us first calculate $GAgent(A_1)$ we order the preference information by score, in this case $Agent_3(A_1) \geq Agent_4(A_1) \geq Agent_1(A_1) \geq Agent_2(A_1)$. Table 4 is useful in the procedure.

Table 4. Each participating agent's importance of alternative 1

$Agent$	$Agent_i(A_1)$	I_i	$u_i=\sum_{k=1}^{i} I_k$	$w_i=(u_i)^2-(u_{i-1})^2$
3	0.7	0.18	0.18	$(0.18)^2-(0)^2=0.03$
4	0.7	0.24	0.42	$(0.42)^2-(0.18)^2=0.15$
1	0.61	0.27	0.69	$(0.69)^2-(0.42)^2=0.3$
2	0.44	0.31	1	$(1)^2-(0.69)^2=0.52$

Using this we obtain

$$GAgent(A_1)=\sum_{k=1}^{n} w_k Agent_k(A_1)$$
$$=(0.7)(0.03)+(0.7)(0.15)+(0.61)(0.3)+(0.44)(0.52)=0.53$$

For A_2 and A_3 are shown inTable 5 and Table 6. Using these we get

$$GAgent(A_2)=\sum_{k=1}^{n} w_k Agent_k(A_2)$$
$$=(1)(0.1)+(0.54)(0.24)+(0.53)(0.33)+(0.5)(0.33)=0.57$$

$$GAgent(A_2)=\sum_{k=1}^{n} w_k Agent_k(A_3)$$
$$=(0.88)(0.1)+(0.86)(0.24)+(0.53)(0.33)+(0.15)(0.33)=0.51$$

Finally, we pick up the largest alternative A_2 to be the group decision.

Table 5. Each participating agent's importance of alternative 2

$Agent$	$Agent_i(A_2)$	I_i	$u_i=\sum_{k=1}^{i} I_k$	$w_i=(u_i)^2-(u_{i-1})^2$
2	1	0.31	0.31	$(0.31)^2-(0)^2=0.1$
1	0.54	0.27	0.58	$(0.58)^2-(0.31)^2=0.24$
4	0.53	0.24	0.82	$(0.82)^2-(0.58)^2=0.33$
3	0.5	0.18	1	$(1)^2-(0.82)^2=0.33$

Table 6. Each participating agent's importance of alternative 3

$Agent$	$Agent_i(A_3)$	I_i	$u_i = \sum_{k=1}^{i} I_k$	$w_i = (u_i)^2 - (u_{i-1})^2$
2	0.88	0.31	0.31	$(0.31)^2 - (0)^2 = 0.1$
1	0.86	0.27	0.58	$(0.58)^2 - (0.31)^2 = 0.24$
4	0.53	0.24	0.82	$(0.82)^2 - (0.58)^2 = 0.33$
3	0.15	0.18	1	$(1)^2 - (0.82)^2 = 0.33$

After making the group decision procedure, we should tune the alternative values for second round. Taking the Eq. (6) the A_2 should be tuning down. In contrast, using the Eq. (7) the A_1 and A_3 should be tuning up. For the tuning constant C = 1/2, we can get the result as below.

$$Agent_1' = \left\{\frac{0.72}{A_1}, \frac{0.34}{A_2}, \frac{1}{A_3}\right\},\ Agent_2' = \left\{\frac{0.52}{A_1}, \frac{0.625}{A_2}, \frac{1}{A_3}\right\},$$
$$Agent_3' = \left\{\frac{0.83}{A_1}, \frac{0.31}{A_2}, \frac{0.5}{A_3}\right\},\ Agent_4' = \left\{\frac{0.83}{A_1}, \frac{0.33}{A_2}, \frac{0.63}{A_3}\right\}.$$

Obviously, A_2 will not be chosen in the second round, but A_1. As a result of each agent's volition has larger conflict, the group decision has greater variation in the next round.

7 Conclusions

In multi-agent decision making environment, each agent has its own concerning factors when he want to make a choice. In this paper, we use the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) to evaluate a problem in the form of a hierarchy. Each agent can flexibly accomplish different hierarchy structure according to its situation as long as these agents have the same selective alternatives.

We have extended the group decision-making process based on collaboration imperative function *h(x)* by allowing the agents to propose its favorite level of each alternative. In some cases, the participating agent may have highly preferred choice and drop the others. To avoid such kind of situation, we suggest ways of modifying the formulation of the group decision functions to discourage strategic manipulation by the participating agents.

In long-term of viewpoint, the group decision cannot always follow the greater part of choice and ignore the others. Hence, we should adapt the values effectively after each round of decision process. It will make the less part of opinions may be picked out after several periods of decision process.

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