Evaluation of Trustworthiness based on Fuzzy Set Theory

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Abstract

In the heterogeneous network, trustworthiness of the entity can help other entities to decide whether or not to have a transaction with it. The feedback data used to evaluate trustworthiness always comes from different entities in different system and is expressed in all kinds of forms. This may be easy for entity to express their trustworthiness, but it will increase difficulties of evaluation of trustworthiness. This paper first introduces different express forms used to show trustworthiness of the entities, and then show how to translate different form into fuzzy form using fuzzy set theory, and give a evaluates of integrated data. The experiment data shows that the trustworthiness expressed with fuzzy form is more appropriate, and the method based on fuzzy set is more convenient for the entities to predict the risk.

Keywords: Trustworthiness, Fuzzy set theory, Evaluation, Reputation

1. Introduction

In the environments of P2P network, grid, semantic network, and other multi agent systems, the entities can interact conveniently with others entities upon these systems, but there are great uncertainty and risk in the online world. Normal, the entities rarely interact with the same party and most occasions they must face the strangers, especially in the large distributed environments. In these systems, before interactions, it is natural for the entities to doubt behavior of the partners. They will evaluate trustworthiness of the partners. One of the ways to minimize threats that the peers exposed to throughout the network is to use trustworthiness information. Such information can help estimating the trustworthiness and predicting the future behavior of entities. As a result, trust and reputation is getting considerable attention in the academic domain and the Internet industry, such as FreeNet [1], P-Grid [2], TrustMe [3], EigenTrust [4] and EigenRep [5], ReGreT [6, 7], PeerTrust [8], FIRE [9], PowerTrust [10] and so on.

Before the entities have a practical interaction, the request entity will evaluate the trustworthiness of the object entities, and this can largely decrease the probability of being attacked and got stuck. There are lots of evaluation models of trustworthiness for multi agent systems to evaluate the trustworthiness of the peers [8, 10-12]. The evaluation data mainly comes from two aspects: one is the interaction history of the peers themselves, and the other is other peers' recommendations. Because interactions frequency between the same entities in big system is very low, most evaluation data comes from the feedback of recommendation from other entities. For the different strategies, information is always expressed in different forms and when the request

entities want to have an integrated evaluation, it is a key matter about how to aggregate with different expression forms data.

In some system, such as centralized environments or particular systems, the entity use the same form to express trustworthiness information, so the ratings are easy to understand for the whole system and can freely adapt to the corresponding evaluation systems. But in other system, such as open decentralized network or the hybrid systems, uniform expression and criterion of evaluation is hard to realize.

Trustworthiness scores or trust measures are important for peers to measure the trustworthiness of the peers. Different systems adopt different expression forms to express trustworthiness, and other systems can't get accurate meanings of the ratings. For example, 1 stands for good reputation and -1 is bad in some systems, such as eBay, and it only uses three numbers to express the evaluation; but in Bayesian system [13], 1 means good and 0 is bad, and the range of trustworthiness is between 0 and 1; and some other systems even using Natural language [14] or evidence theory [15] have the same matters. This maybe lead to the big matter for evaluation, and only with the uniform expression, the ratings can take good use of and work better.

Through more than half century, fuzzy set theory has been using all kind of application, and has become a mature branch of the mathematics. The most important feature of fuzzy set is that it can easily depict and simulate human thinking, measure and recognize the subjective trust, and it also can be used to infer and make decision. This paper uses fuzzy set theory to express and evaluate trustworthiness of the entities. The reason is twofold: first, it is difficult to use probability to depict subjectivity and imprecision of trustworthiness information, and it is also difficult to make sure of the independent of the events in beta systems and Bayesian probability [16] systems, but it is easy to go through it in fuzzy set theory. For example, [0, 1] is used to express trustworthiness in many models, if 0.5 stands for the medium, then is 0.51 a little more trust? Is 0.49 untrusted? It is unfair and unsuitable to use fixed threshold, and it can't get accurate evaluation results, but it is different for fuzzy set theory to use membership function, it can reveal much more information, so it can solve the matter mentioned above, and it can predict the trend of the behavior, this is more important for the system.

We will give a particular description below about how to use membership function to express trustworthiness information with fuzzy and subject features, and how to translate information expressed with different forms into a unified form, and how to use fuzzy set theory to efficiently evaluate trustworthiness of the entities. The whole paper is arranged as follows: Section 2 is related work; Section 3 introduces the expression forms of trustworthiness and their evaluations, and in Section 4 gives a detail description about how to translate these different forms into the same form; Section 5 evaluates trustworthiness of the entities using the fuzzy number based on the fuzzy set theory; last section gives the conclusions.

2. Related Work

Evaluation of trustworthiness isn't a new problem, and it has lay enough store by many scientists. Based on Beta probability density function, Josang [13] proposed a Beta reputation system integrated the feedback ratings. Lik Mui [17] *et al.*, proposed a rating system based on Bayesian probability. There are some other literatures [16, 18, 19] importing fuzzy theory into the computational model of the reputation. Fuzzy method was used in many literature [18] to evaluate trustworthiness of the service provider, and data sources including: interaction trust, reputation of witness and reputation of certificate. H. Q. Lin [20] *et al.*, used layered fuzzy

trust management to quantify trustworthiness in e-commerce systems. L. F. Xu [21] *et al.*, adopted fuzzy set theory to compute trustworthiness and solved the problem about model. Although it seems intuitive, the evaluation is curtly. A. W. Ma [22] *et al.*, classified the trust with fuzzy set methods and used the fuzzy input, so it reduced the range of error between the quantity evaluations. F. J. Yu [23] *et al.*, proposed a fuzzy relationship model using recommendation in P2P environments, and got the integrated of a computational reputation model. The proposed model can largely prevent malicious resource peers and malicious recommendation behaviors. Literature [24] used fuzzy logic and inferred trustworthiness with uncertainty and imprecision, and the authors proposed four definitions about degree of trustworthiness: distrust, undistrust, untrust and trust. Literature [25] used fuzzy set deal the trust relationship in semantic network.

When evaluating trustworthiness of the entities, we should take some measures to change information into the uniform and integrate them into the evaluation, or it will increase degree of difficulty.

3. Different Forms of Trust Information

To the most models about trust, the first step is to settle the matter of how to express trust information. A representation with high expressiveness will add complexity to the aggregation and some other steps. And a representation with low expressiveness will limit the effectiveness of the trust mechanism [26]. Some trust models using different forms to show trust, Shown as Figure 1. The entities must evaluate and anticipate trustworthiness of the other entity before they have interactions. But trust data they received is always expressed in different forms, and they must translate these data into a uniform so as to they can aggregate the data to get trustworthiness of the potential opposite partners.
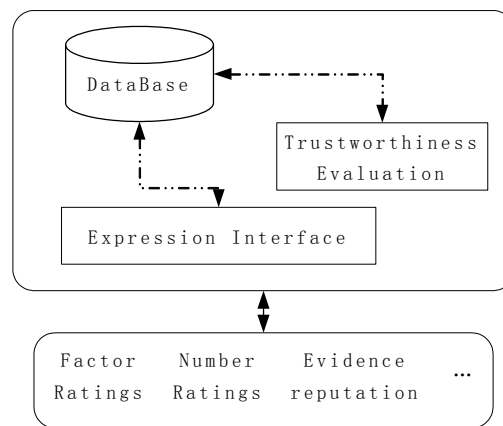

Figure 1. Different Forms of Reputation Information

3.1. Factor Form

Factor form is a form that adopts finite numbers to show trustworthiness about partners, and different factors stand for different degree of trustworthiness. Such as eBay, it only uses three numbers (-1, 0 and 1) to mean positive rating, neutral rating and negative rating respectively. After every transaction, the partners will give the ratings each other which will be available to the future potential transaction partners. To the present, this seems enough for users to give an evaluation for potential partners. There are some other systems using factor

forms to show the ratings, such as natural language, which uses very good, good, bad, and very bad to show their trustworthiness, or numbers, like 1, 2, 3, 4, and 5. The factor form is very simple and convenient to use for all users, but it can't be used in the complex computable models.

3.2. Bayesian Probability Form

Bayesian probability form is used to statistically update by binomial or multinomial Dirichlet [27] probability density function. Posteriori probability of binomial can be a distribute of Beta, and probability density function is written as f(p|α, β), and use Γ(gamma function) as follows:

$$f(p \mid \alpha, \beta) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} p^{\alpha-1}(1-p)^{\beta-1}$$

where $0 \leq p \leq 1$; and if $\alpha < 1$, then $p \neq 0$; if $\beta < 1$, then $p \neq 1$.

If we analyze the result and using r standing for the number of success and s is the number of failure, let $\alpha = r+1$, and $\beta = s+1$, where r and s are both greater than 0. According to probability density function, entity X can get the expectation of probability density function of the object entity T as follow:

$$E(f(p \mid r_T^X, s_T^X)) = \frac{(r_T^X + 1)}{(r_T^X + s_T^X + 2)},$$

so the trustworthiness rating of the entity T be got as follow:

$$rep(r_T^X, s_T^X) = E(f(p \mid r_T^X, s_T^X) - 0.5) * 2 = \frac{(r_T^X - s_T^X)}{(r_T^X + s_T^X + 2)}$$

Bayesian form bases on statistic mathematics, but it has some deficiencies, for example, it can't differentiate two situations: the new joiner with medium rating at the beginning and the entity with the medium rating after many transactions, and this is unfair. Furthermore, it is difficult to completely ensure independent of the events.

3.3. D-S Evidence Theory Form

D-S evidence theory is a mature theory and has been widely used in artificial intelligence domain, and it's a general Bayesian probability. Yu and Singh [15] used D-S evidence theory to express trustworthiness information. Its universe of discourse is $\Theta = \{T, \neg T\}$, and probability density function is m: $2^\Theta \mapsto [0, 1]$, where:

(1) $m(\Phi) = 0$;

(2) $\sum_{\hat{A} \subset \Theta} m(\hat{A}) = 1$, so $m(T) + m(\neg T) + m(\theta) = 1$, where $m(T)$, $m(\neg T)$ and $m(\theta)$ respectively stand for support degree of trust, untrust and ignorance, and it uses function Bel(A) to decide on trust or untrust: Bel({T})=m({T}), and Bel({¬T})=m({¬T}).

3.4. DSmT Evidence Theory Form

DSmT expands D-S evidence theory, and it includes situation of ignorance and conflict evidences [26]. DSmT defines a general probability function: $D^\Theta \mapsto [0,1]$, where:

(1) $m(\Phi) = 0$;

(2) $\sum_{\hat{A} \subset D^\Theta} m(\hat{A}) = 1$, so $m(T) + m(\neg T) + m(\theta) + m(T \cap \neg T) = 1$, where $m(T)$, $m(\neg T)$, $m(\theta)$ and $m(T \cap \neg T)$, and they respectively stand for support degree of trust, untrust, ignorance and conflict evidences, and $Bel(A) = \sum_{B \subseteq A, B \in D^\Theta} m(B)$, so Bel({T})= m({T})+m({T∩¬T}), and Bel({¬T})= m({¬T})+m({T∩¬T }).

Comparing with D-S theory, DSmT evidence theory can deal with conflict evidences, but efficiency is lower than D-S theory when conflict is small.

3.5. Fuzzy Set Form

In 1965, the expert of computer and cybernetics first proposed definition of fuzzy set theory, and it is a good expansion of Gantor set theory. Fuzzy logic specially deals with uncertainty and imprecise information using membership function with high efficiency, and membership function show degree of variable belonging to the set. Integer number 1 shows completely belonging to the set and number 0 shows completely not belonging to the set, and other variable mean the degree of belonging to. Fuzzy set can be defined as follow:

Definition 1: Let $\tilde{A}$ as a map of universe of discourse X to set [0, 1], namely $\tilde{A}$: X→[0, 1], $x \mapsto \tilde{A}(x)$. $\tilde{A}$ is a fuzzy set, $\tilde{A}(x)$ is membership function of $\tilde{A}$, or x shows as the degree of membership of $\tilde{A}$.

Some literatures introduced lots of the methods to aggregate information using fuzzy set theory described in related work. They not only use fuzzy set to express trustworthiness information, but also aggregate them using fuzzy logic.

4. Translation of Different Forms into a Uniform

We need translates different expression form into a uniform, shown as Figure 2, and then the system can make an evaluation. With uniform expression, trustworthiness evaluation model can deal with them and get the integrated reputation.

4.1. Translation of Factor Form

If there are limited factors to show trustworthiness information, we can use Zadeh in fuzzy set, where $\tilde{A}$ means "the trustworthiness of the entities". The ratings can be -1, 0 and 1 in eBay, and we can express them as follow: $\tilde{A} = \frac{0}{-1} + \frac{0.5}{0} + \frac{1}{1}$, the trustworthiness is 0 when the rating is -1, that is completely untrustworthy; and the trustworthiness is 0.5 and 1 when the rating is 0 and 1. We use the same way to define "very good", "good", "normal", "bad", "very bad", so $\tilde{A} = \frac{1}{very\ good} + \frac{0.75}{good} + \frac{0.5}{nomal} + \frac{0.25}{bad} + \frac{0}{very\ bad}$.

So if the number of the factor is n, and they respectively are: θ_1, θ_2,...,θ_i,...,θ_n, then

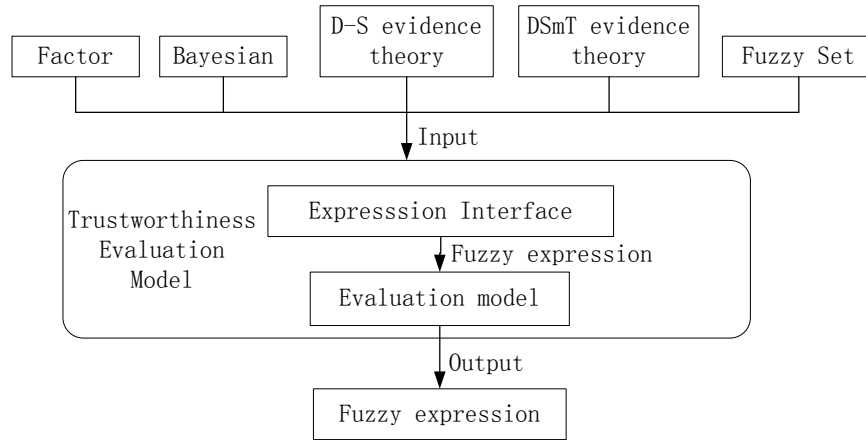$$\tilde{A} = \sum_{i=0}^{n-1} \frac{i}{n-1} * \frac{1}{\theta_{i+1}} .$$

Figure 2. Different Expression Forms are Translated into a Uniform

4.2. Translation of Bayesian Form

Bayesian method uses "opinion" to express trustworthiness, and the opinion gave by entity A to entity X is $w_x^A = (b + d + u)$, where b, d and u are respectively standing for trust, untrust and ignorance, where $b = r/_{r+s+2}$, $d = s/_{r+s+2}$, $u = 2/_{r+s+2}$. Using fuzzy set to express trustworthiness, if Ã as "the trustworthiness of the entities", then the fuzzy set expression gave by entity A is defined as follow:

$$\mu_{\tilde{A}}(rep\,(r_T^X, s_T^X)) = \int_{\tilde{A}} \frac{b}{rep\,(r_T^X, s_T^X)} = \int_{\tilde{A}} \frac{1}{rep\,(r_T^X, s_T^X)} * \frac{r_T^X}{r_T^X + s_T^X + 2}.$$

4.3. Translation of Evidence Theory Form

D-S and DSmT, as typical evidence theory methods, can use uniform with fuzzy set. According evidence theory, support degree of evidence A can be defined as m(A), and the trustworthiness is defined as Bel(A), so we can translate them into a uniform with membership function of fuzzy set. Typical evidence is only two, and they respectively are T and ¬T, then Bel({T})= m({T})+m({T∩¬T }) or Bel({¬T})= m({¬T})+m({T∩¬T }). So if Ã is "the trustworthiness", then the membership function of the fuzzy set is:
$\tilde{A} = \frac{Bel\,(\{T\})}{\{T\}} + \frac{Bel\,(\{\neg T\})}{\{\neg T\}}$.

After information is expressed with unified form, we can use fuzzy set theory to analyze them and give a centralized computing. We need unify the universe of the discourse of different fuzzy set again.

4.4. Uniform and Fuzzy Vector

In some systems, they always claim the users to give a rating in a certain range after transaction. For example, if the ratings is between at the range of [M_1, M_2], then we set $K = \frac{M_2 - M_1}{2 * M}$, and the trustworthiness can be respectively descript as: "very low", "low", "medium", "high", "very high", and we can compute and set the echelon areas defined as:

$(1) [M_1, k + M_1, \frac{5}{2}k + M_1]$;

$(2) [\frac{3}{2}k + M_1, \frac{5}{2}k + M_1, \frac{7}{2}k + M_1, \frac{9}{2}k + M_1]$;

$(3) [\frac{7}{2}k + M_1, \frac{9}{2}k + M_1, \frac{11}{2}k + M_1, \frac{13}{2}k + M_1]$;

$(4) [\frac{11}{2}k + M_1, \frac{13}{2}k + M_1, \frac{15}{2}k + M_1, \frac{17}{2}k + M_1]$;

$(5) [\frac{15}{2}k + M_1, 9k + M_1, M_2]$.

The membership functions are respectively shown as Figure 3 and Figure 4, where the universe of discourse are respectively [0, 1] and [0,100].
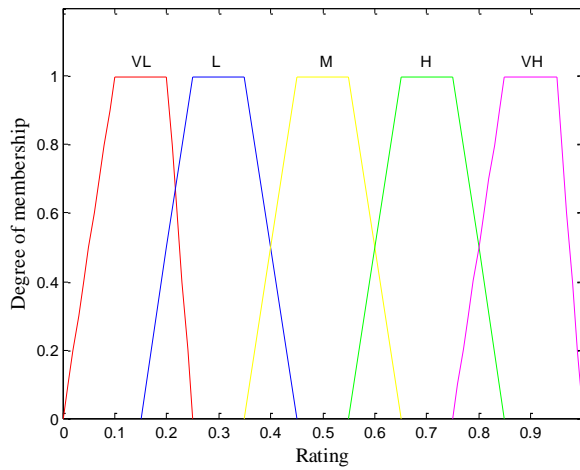

Figure 3. The Relationship between Membership Function and Universe of Discourse ([0,1])
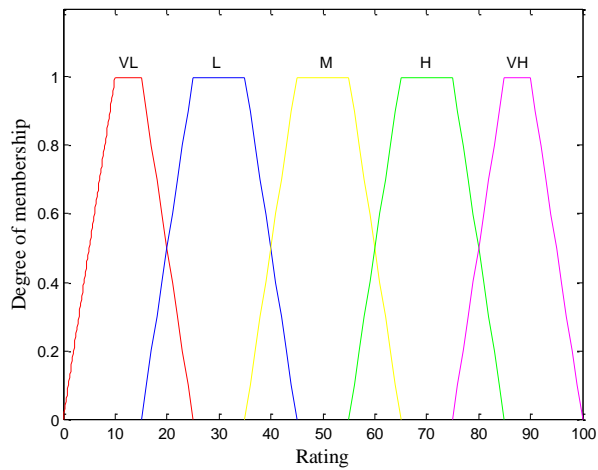

Figure 4. The relationship between Membership Function and Universe of Discourse ([0, 100])

These membership functions can be translate into the form of fuzzy vector, shown as figure 5. If the ratings is between [-1, 1], the area is divided into five parts: [-1, -0.8, -0.5], [-0.7, -0.5, -0.3, -0.1], [-0.3, -0.1, 0.1, 0.3], [0.1, 0.3, 0.5, 0.7], [0.5, 0.8, 1]. If the rating of some entity is -1, the corresponding fuzzy vector is defined as (1 0 0 0 0); If the rating is 0, the fuzzy vector can be defined as (0 0 1 0 0), accordingly, if the ratings are 1, 0.2 and 0.6, the corresponding fuzzy vector can be respectively defined as (0 0 0 0 1), (0 0 1/2 1/2 0) and (0 0 0 1/2 10/3).
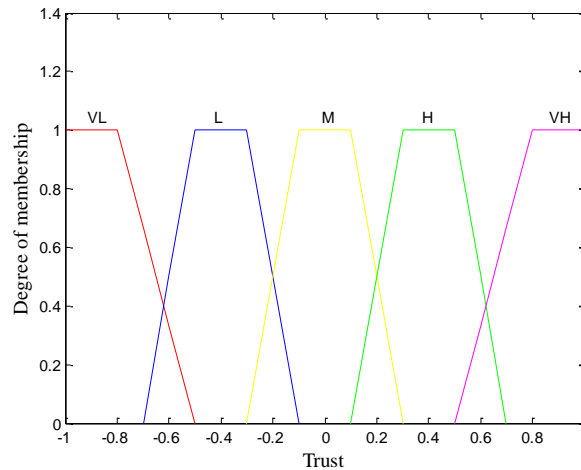

Figure 5. The Relationship between Membership Function and the Universe of Discourse ([-1, 1])

5. Integrated Evaluation of Trustworthiness

5.1. The Process of Evaluation

The steps of the evaluation can be divided into three steps:
(1) Build fuzzy set $\tilde{A}$;
(2) Build evaluation matrix R;
(3) Integrated evaluation.

Different ratings of the trust can be respectively defined as different membership function, suppose the number of the fuzzy set is M, they are $\tilde{A}_i$ (i=1,…,M), when M=5, they can be defined as: Very Low, Low, Medium, High, Very High with different membership function.

Definition 2: For entity X, the trustworthiness vector of entity X, rated by other entities Xi, is $R_i=(r_{1i},r_{2i},r_{3i},r_{4i},r_{5i})^T$, where $r_{ji}(j=1,2,…,5)$ means the degree of different fuzzy set $\tilde{A}_j$.

So the ratings compose a fuzzy matrix:

$$R = (R_1 \quad R_2 \quad … \quad R_i \quad … \quad R_m) = \begin{vmatrix} r_{11} & r_{12} & … & r_{1i} & … & r_{1m} \\ r_{21} & r_{22} & … & r_{2i} & … & r_{2m} \\ r_{31} & r_{32} & … & r_{3i} & … & r_{3m} \\ r_{41} & r_{42} & … & r_{4i} & … & r_{4m} \\ r_{51} & r_{52} & … & r_{5i} & … & r_{5m} \end{vmatrix}$$

The integrated functions are: weighted sum, geometry average, decide on by single factor, decide on by main factor or fuzzy evaluation, this paper uses the fuzzy number to evaluate.

Suppose the weights are $A_i \in [0,1]$, if $A_1 R_1 + A_2 R_2 + ... + A_n R_n = \sum_{i=1}^{n} A_i R_i$, and

$A_1 + A_2 + ... + A_n = \sum_{i=1}^{n} A_i$, then $\sum_{i=1}^{n} A_i R_i$, $\sum_{i=1}^{n} R_i \in \tilde{\Re}$.

Theorem [28]: suppose $A_i, R_i \in Supp\ (A_i)$, $0 \in Supp\ (\sum_{i=1}^{n} A_i R_i)$, $C = \sum_{i=1}^{n} A_i R_i \div \sum_{i=1}^{n} A_i$, $a \in (0,1]$,

marks $C_a = [C_a^{(1)}, C_a^{(2)}]$, $(A_i)_a = [a_{ia}^{(1)}, a_{ia}^{(2)}]$, $(R_i)_a = [r_{ia}^{(1)}, r_{ia}^{(2)}]$, $i = 1, 2, ..., n$, then

(1) $C_a^{(1)} = \dfrac{\sum_{i=1}^{n} a_{ia}^{(i_k)} r_{ia}^{(1)}}{\sum_{i=1}^{n} a_{ia}^{(i_k)}}$, and when $r_{ia}^{(1)} \geq C_a^{(1)}$, $i_k = 1$; when $r_{ia}^{(1)} < C_a^{(1)}$, $i_k = 2$. If there is i, make

$R_i(r_{ia}^{(1)}) = a$ or $A_i(a_{ia}^{(i_k)}) = a$, then $C(C_a^{(1)}) = a$;

(2) $C_a^{(2)} = \dfrac{\sum_{i=1}^{n} a_{ia}^{(i_l)} r_{ia}^{(2)}}{\sum_{i=1}^{n} a_{ia}^{(i_l)}}$, and when $r_{ia}^{(2)} \geq C_a^{(2)}$, $i_l = 2$; when $r_{ia}^{(2)} < C_a^{(2)}$, $i_l = 1$. If there is i, make

$R_i(r_{ia}^{(2)}) = a$ or $A_i(a_{ia}^{(i_l)}) = a$, then $C(C_a^{(2)}) = a$. C is the integrated evaluation.

Suppose $(v_1, v_2, ..., v_n) \in V^n$, and $W = (w_1, w_2, ..., w_n) \in [0,1]^n$, where W≠0, then $\exists i \in \{1,2,..., m\}$, let

$w_i \neq 0$, marks $g_w(v_1, v_2, ..., v_n) = \dfrac{\sum_{i=1}^{n} w_i v_i}{\sum_{i=1}^{n} w_i} = \bar{v}$ utilizes extended theory:

$$C(v) = \bigvee_{g_w(v_1, v_2, ..., v_n) = v} [(\bigwedge_{i=1}^{n} A_i(w_i)) \wedge (\bigwedge_{i=1}^{n} R_i(v_i))], \ \forall v \in V$$

5.2. Experiment

We use the data from figure 3 and figure 4 to evaluate, and the data in Figure 3 stands for the membership function of the ratings, and the data in Figure 4 stands for the membership function of weight. According to the theorem above, we set a=0, 0.25, 0.5, 0.75 and 1 respectively.

When a=0:

$(R_1)_0 = [0, 0.25]$, $(R_2)_0 = [0.15, 0.45]$, $(R_3)_0 = [0.35, 0.65]$, $(R_4)_0 = [0.55, 0.85]$, $(R_5)_0 = [0.75, 1]$

$(A_1)_0 = [0, 25]$, $(A_2)_0 = [15, 45]$, $(A_3)_0 = [35, 65]$, $(A_4)_0 = [55, 85]$, $(A_5)_0 = [75, 100]$

As $r_{1,0}^{(1)} = 0 < r_{2,0}^{(1)} = 0.15 < r_{3,0}^{(1)} = 0.35 < r_{4,0}^{(1)} = 0.55 < r_{5,0}^{(1)} = 0.75$, so $w_1 = a_{1,0}^{(2)} = 25$, $w_5 = a_{5,0}^{(1)} = 75$.

As (25+75)*0.15 < (25*0+75*0.75), (25+75)*0.55 < (25*0+75*0.75), so $w_2 = a_{2,0}^{(2)} = 45$, $w_4 = a_{4,0}^{(2)} = 85$.

As (25+45+85+75)*0.35 < (25*0+45*0.15+85*0.55+75*0.75), so $w_3 = a_{3,0}^{(2)} = 65$.

$$C_0^{(1)} = \frac{25 * 0 + 45 * 0.15 + 65 * 0.35 + 85 * 0.55 + 75 * 0.75}{25 + 45 + 65 + 85 + 75} = 0.449153 \approx 0.449$$

$$C_0^{(2)} = \frac{0 * 0.25 + 15 * 0.45 + 35 * 0.65 + 55 * 0.85 + 100 * 1}{0 + 15 + 35 + 55 + 100} = 0.859756 \approx 0.860$$

With the same process of the computing, we can get the results when a= 0.25, 0.5, 0.75 and 1 repectively, shown as Table 1:

Table 1. Result of Evaluation

a	$C_a^{(1)}$	$C_a^{(2)}$
0	0. 449	0. 860
0. 25	0. 483	0. 824
0. 5	0. 518	0. 790
0. 75	0. 553	0. 756
1	0. 589	0. 722

According to table 1, we can draw the membership function of the evaluation, shown as Figure 6, and between [0.449, 0.599] and [0.722, 0.860], then C(v) is almost the beeline, and the integrated evaluation is between 0.599 and 0.722, the highest is 0.86 and the lowest is 0.449.
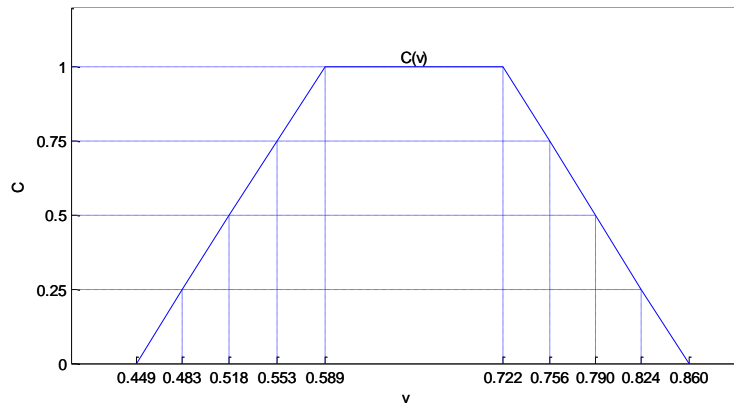

Figure 6. Membership Function of the Integrated Evaluation

5.3. Comparison

Using other methods to compute the reputation, like literature [21] and eBay, the last reputation is the number of positive rating minus the number of negative rating. In the process of the integration, a lot of the reputation information is lost, and through comparing to the threshold to decide whether or not to have a transaction. So when the threshold is 0.70, the results of the evaluation will be different if the reputation ratings are 0.69 and 0.71. But the mode is different in this paper if using fuzzy set theory, the fuzzy expression form not only consists to the definition of the reputation, but also embodies the fairness, and there isn't lost information. From other point, the last evaluation result includes the whole evaluation of the whole network, and it's convenient for the entity to evaluation the object entity.

6. Conclusion

The definition of fuzzy set can easily settle the problem of fuzziness and uncertainty, from this points, it is feasible to express and evaluate trustworthiness of the entities. We analyze the ratings using fuzzy set theory, and translate the different form ratings into the uniform, and use fuzzy number to evaluation trustworthiness of the entities. The experiments show that it has more fair results. Although the fuzzy set theory has become a mutual mathematic path, it needs the deep research about how to take good use of the fuzzy set theory to the computational of the reputation, and how to use it to measure, recognize, infer and rating the decision, realize the integrated evaluation with high efficiency and accuracy.

Acknowledgements

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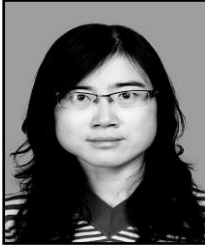
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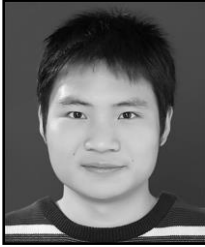
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