Fuzzy Hierarchical Weight Analysis for Criteria of the Taiwan National Quality Award

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Abstract

In this paper, fuzzy hierarchical weight analysis (FHWA) is used to explore the process by which the criteria weights of the Taiwan National Quality Award (TNQA) are assigned by TNQA committee members. Each member is allowed to employ fuzzy scales in place of exact scales. Each pairwise comparison of criteria is made through a questionnaire from each TNQA committee member. The membership function of trapezoidal fuzzy numbers is introduced to specify TNQA committee members’ intentions. After the defuzzification for each pairwise comparison matrix, seven nonqualified respondents are excluded from further analysis. After FHWA, the reasonable range of each criterion weight of TNQA is determined. The current distribution of criteria weights of TNQA is justified. The details of FHWA are discussed in this paper.

Key words: AHP, TNQA, Fuzzy Hierarchical Weight Analysis.
Introduction

In recent years, there have been many national quality awards (NQAs) established in different countries around the world. One important common reason for establishing such NQAs is to build up a business model of excellence based on total quality management (TQM) to provide better products or services, but at a lower price than those of competitors. For each country involved, the NQA is a critical systematic approach to enhancing national competitiveness. The establishment of the Deming Award in 1950 played an important role in the creation of the Japanese economic miracle. It encouraged Japanese quality and facilitated Japan becoming a significant nation in global economics, to the extent that it became a threat to the economic power of several leading industrial countries, including the United States and European countries. As a result, an increasing number of countries have established NQAs to improve their own competitiveness in terms of quality.

In most countries, professional institutes, some of which are under partial government control, are in charge of the NQAs. To provide credibility and ensure justice in the awarding of NQAs, recognized quality experts are usually invited to design the criteria for the awards and to evaluate the quality improvement of businesses involved. Criteria are designed to provide for a high standard of quality for those organizations that are keen to pursue the highest levels of performance in TQM. For example, the criteria of the Malcolm Baldrige National Quality Award (MBNQA) (NIST, 2001) are designed to help organizations use an aligned approach to organizational performance management that results in the delivery of ever-improving value to customers, contributes to marketplace success, improves overall organizational effectiveness and capabilities, and enhances organizational and personal learning. Similarly, the criteria of Taiwan National Quality Award (TNQA) are based on following premises (CSD, 2001):

1. **Generality**: the criteria are designed to cover as many kinds of organizations as possible.

2. **Prospective**: the criteria recognize the trends of the modern age and encourage prospective thinking within organizations.

3. **Integration**: the criteria cover the main concepts, content, processes, and performance evaluations of TQM, and pursue excellence of performance in terms of integration. The seven categories of the TNQA are correlated with each other and are inseparable.

4. **Internationalism**: In 2001, the criteria of TNQA were modified, based on the 2000 Malcolm Baldrige Award, the 1998 Deming Award, the 1999 European Quality Award, and
ISO 9000-2000. They not only meet domestic requirements, but also keep pace with global trends in TQM.

5. **Operational**: The criteria of TNQA are focused on increasing efficiency and effectiveness, and on improving productivity and performance. Taken together, they represent a practical benchmark for organizations engaged in the pursuit of excellence.

In summary, the NQA criteria specify all the conditions required to attain quality excellence, and are coherently interrelated.

The TNQA has been successfully conducted for thirteen years since it was established in 1990. In response to the advent of e-commerce and the knowledge economy, the criteria of TNQA have been modified, involving a reduction from nine categories to seven. The seven categories are listed in Table 1.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Leadership</td>
<td>0.15</td>
</tr>
<tr>
<td>II. Innovation and strategic management</td>
<td>0.11</td>
</tr>
<tr>
<td>III. Customer and market development</td>
<td>0.11</td>
</tr>
<tr>
<td>IV. Human resource and knowledge management</td>
<td>0.11</td>
</tr>
<tr>
<td>V. Information management</td>
<td>0.11</td>
</tr>
<tr>
<td>VI. Process management</td>
<td>0.11</td>
</tr>
<tr>
<td>VII. Business result</td>
<td>0.30</td>
</tr>
</tbody>
</table>

As can be seen in Table 1, each category is assigned a weight to stress its importance. The question of the weighting value assigned to each category is interesting. Are the weightings reasonable as an adequate evaluation system for those organizations interested in competing for the TNQA? Although it is not possible to know exactly how committee members of the TNQA came to assign the weightings, the adequacy of such weightings can be verified through questionnaire investigation. The present study employs the fuzzy analytical hierarchical process (FAHP) to ascertain, via a questionnaire, a reasonable range of weights for the TNQA criteria for each category according to the perspective of committee members of the TNQA.

**AHP and related works**

During the past two decades, the analytical hierarchical process (AHP), which was introduced by Saaty (1980), has become one of the most widely used methods for the practical solution of multi-criteria decision-making (MCDM) problems. Generally, the AHP has been
applied from daily problems to more complicated problems such as evaluating the implementation of a maintenance system (Labib et al., 1998), selecting electric power plants (Akash et al., 1999), and evaluating weapon systems (Cheng & Mon, 1994). The AHP enables decision-makers to structure a complex problem in the form of a simple hierarchy and to evaluate a large number of quantitative and qualitative factors in a systematic manner under conflict criteria. In the hierarchy, the overall goal is situated at the highest level; elements with similar features are grouped at the same middle level and decision variables are located at the lowest level. Then, a series of pairwise comparisons is made among the elements at the same level using the ratio scales 1, 3, 5, 7, and 9, as suggested by Saaty (1980). Judgment matrices are then formulated for all evaluation criteria, and the relative weights of the criteria are estimated by calculating the eigenvalues for the judgment matrices with these relative weights aggregated and synthesized for the final measurement of given decision alternatives.

The AHP has been extensively used in group decision-making. However, the scale of pair comparisons among criteria is restricted to those that are crisp (Chen, 1996; Hauser & Tadikamalla, 1996). In other words, the decision-makers are assumed to be precise in their minds regarding comparisons among criteria. However, in the real world, many situations are generally fuzzy rather than being clear in terms of decision-making. Examples include evaluating personality, past experience, and self-confidence. In such cases, the comparisons or measurements among criteria made by decision-makers are subjective and psychological. This creates a situation of imprecise value that drives the questions into fuzziness. The process of evaluation under these circumstances should involve fuzzy identification, and the AHP should be modified to fit this reality. To overcome these shortcomings, the principle of fuzzy logic was introduced into the AHP for MCDM (Jung & Lee, 1991; Levy & Ke, 1998). This makes it possible to adapt the AHP in an environment in which the input information, or the relations among criteria and alternatives, are uncertain or imprecise.

**Fuzzy hierarchical weight analysis**

The general AHP procedure can be summarized as follows:

- constructing the hierarchical relationship structure for the problem;
- developing pairwise comparison matrices for the hierarchical relationship structure;
- determining the weights of criteria for each hierarchy and checking consistency among pairwise comparison matrices; and
- calculating and ranking the relative weight scores for each alternative.
In this paper, the decision process involves fuzziness for decision-makers. The proposed fuzzy hierarchical weight analysis procedure, based on AHP procedure applied to the criteria of the TNQA, is described as follows in eight detailed steps.

**Step 1. Hierarchical structure for determining criteria weights of TNQA**

To apply FAHP, the opinions of TNQA committee members in determining the TNQA criteria weights have to be structured into hierarchical levels. The hierarchical structure is shown in Figure 1. In Figure 1, the goal is determining criteria weights of TNQA", and seven TNQA criteria are located in this category level.

![Hierarchical structure for determining criteria weights of TNQA](image)

**Step 2. Fuzzy representation of pairwise comparison**

Traditionally, in the AHP, the decision-maker judgments assigned to each criterion comparison can be represented by linguistic variables, as shown in Appendix A. In this paper, the TNQA committee members were allowed to choose crisp numbers’ or intervals’ showing their recognition of criteria comparisons to reflect the real decision situations. For example, in Appendix A, suppose a TNQA committee member is asked to compare the importance of criterion I as compared with that of criterion II. He or she thinks that criterion I is somewhat more important than criterion II. He or she might be unsure as to whether to assign a 3, a 4, or a 5. Choosing the interval from 3 to 5 can represent his or her intention in this uncertain situation.
Thus, the fuzzy numbers are introduced into data collection for this study. The present study adopts Buckley (1985) definition of a fuzzy number as a fuzzy subset of R described by

\[(\alpha / \beta, \gamma / \delta)\]

where \(\alpha, \beta, \gamma,\) and \(\delta\) are real numbers and \(\alpha \leq \beta \leq \gamma \leq \delta\). The graph of the membership function \(\mu\) is determined by these four numbers as follows: (i) zero to the left of \(\alpha\); (ii) continuous and strictly increasing from \((\alpha, 0)\) to \((\beta, 1)\); (iii) a horizontal line segment from \((\beta, 1)\) to \((\gamma, 1)\); (iv) continuous and strictly decreasing from \((\gamma, 1)\) to \((\delta, 0)\); and (v) zero to the right of \(\delta\). In this study, the fuzzy numbers used by TNQA committee members have \(\alpha, \beta, \gamma, \delta, \in \{0, 1, 2, \ldots, L\}\), for \(L\) a positive integer, and the graph of \(\mu\) is a straight line segment over the intervals \([\alpha, \beta]\) and \([\gamma, \delta]\). If two of the numbers \(\alpha, \beta\) or \(\beta, \gamma\) or \(\gamma, \delta\) are equal, the corresponding line segment does not exist. The graph of this membership function is trapezoidal, as shown in Figure 2.

![Figure 2. Membership function of a trapezoidal fuzzy number \((\alpha / \beta, \gamma / \delta)\)](image)

**Step 3. Consistency ratio test for each fuzzy pairwise comparison matrix**

Each committee member was allowed to make a comparison between only two criteria for each question in Appendix A. After finishing the questionnaire, a contra verdict might have occurred within pairwise comparisons. It was necessary to check the whole consistency of relative importance among criteria. Saaty (1980) suggested consistency ratio (CR) to evaluate the consistency of pairwise comparisons in a matrix among criteria, and suggested CR \(\leq 0.1\) was acceptable. CR was defined as:

\[CR = \frac{CI}{RI}\]

where \(CI\) (consistency index) = \((\lambda_{max} - n) / (n-1)\). Here, \(\lambda_{max}\) is the maximum eigenvalue of the pairwise comparison matrix of criteria, and \(n\) is the number of criteria. RI (random index)
means CI values in a different order of hierarchical structure according to the research of the Dak National Laboratory and the Wharton School on evaluating positive reciprocal matrices with a scale of 1 to 9 (Deng, 1989). They are shown as follows.

Table 2. Table of random index

<table>
<thead>
<tr>
<th>order</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.I</td>
<td>0.00</td>
<td>0.00</td>
<td>0.58</td>
<td>0.90</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
<td>1.45</td>
<td>1.49</td>
<td>1.51</td>
<td>1.48</td>
<td>1.56</td>
<td>1.57</td>
<td>1.58</td>
</tr>
</tbody>
</table>

However, each TNQA committee member was allowed to express his or her fuzzy answer using ‘interval’ responses to questions. It was therefore necessary to transform ‘interval’ responses into ‘crisp numbers’ for fuzzy comparison matrices, by defuzzying skill while determining CR value.

The fuzzy set is converted into a crisp value that, in a sense, is the best representative of the fuzzy set. This conversion is called a defuzzification (Klir, 1995). A defuzzification is most commonly used in fuzzy controller operating. In the present study, this technique is used to transform ‘interval’ values into acceptable ‘crisp’ values. There are several defuzzification methods leading to distinct results proposed in the literature. Each method, of course, is based on a specific rationale. Among these defuzzification methods, three have been predominant in the literature on fuzzy control. They are: (i) center of area method; (ii) center of maxima method; and (iii) mean of maxima method. This study uses the mean of maxima method to defuzzify each fuzzy comparison matrix because it is easier to obtain defuzzified value for trapezoidal membership function. The mean of maxima method is described as follows (Klir, 1995).

\[
d_{MM}(C) = \frac{\sum_{Z_k \in M} Z_k}{|M|}
\]

where |M| is the number of members of the crisp set M. In this method, which is usually defined only for the discrete case, the defuzzified value, \(d_{MM}(C)\) is the average of all values in the crisp set M defined by \(M = \{Z_k | C(Z_k) = h(C)\}\).

Step 4. Determining fuzzy maximum eigenvalue

Because the comparison matrix involved fuzzy numbers inside, the fuzzy eigenvalue of the matrix should be expected. A fuzzy eigenvalue is a fuzzy number solution to
\[ \bar{A} \bar{x} = \lambda \bar{x} \]  
(1)

where \( \bar{A} \) is a \( n \times n \) matrix containing fuzzy numbers and \( \bar{x} \) is a non-zero \( n \times 1 \) vector containing fuzzy numbers. In this paper, a bar is placed over a symbol if it represents a fuzzy quantity.

Define
\[ \Omega(A) = \{ \lambda | \lambda A \geq \lambda x, \text{some } x > 0 \} , \text{ and let } \lambda_m = \sup \Omega(A). \]

Here the eigenvalue \( \lambda_m \) is called the ‘dominant’ or ‘maximum’ eigenvalue of \( A \) (Buckley, 1990). \( A \) is assumed to be irreducible. \( A \) is reducible if and only if there is a permutation matrix \( P \) so that
\[ PA = [A_1 | A_2 | A_3] \]
(2)

where \( A_1 \) and \( A_2 \) are square; otherwise \( A \) is reducible. Taking \( \alpha \)-cuts of equation (1) with \( \lambda_m \) gives
\[ (\bar{A} \bar{x})^\alpha = (\lambda_m \bar{x})^\alpha \quad 0 \leq \alpha \leq 1 \]
(3)

Because \( \bar{A} \) contained a trapezoidal fuzzy number, then \( a_{ij} \) the element of \( \bar{A} \) can be expressed as \((a_{ij}^0 / a_{ij}^1, a_{ij}^1 / a_{ij}^0)\) (see Figure 3) so does \( \lambda_m \), that is,
\[ \lambda_m = (\lambda_m^0 / \lambda_m^1, \lambda_m^1 / \lambda_m^0) \].

According to the Perron-Frobenius theorems (Gantmacher, 1959; Karlin, 1959; Lancaster, 1968), we know \( \lambda_m^\alpha \leq \lambda_m^\alpha \). If \( \bar{A} \geq 0, \bar{x} \geq 0, \lambda_m \geq 0 \), and \( 0 \leq \alpha \leq 1 \), then equation (3) becomes
\[ \sum_{j=1}^{n} a_{ij}^\alpha x_{ij}^\alpha = \lambda_m^\alpha x_{ij}^\alpha \quad 1 \leq i \leq n \]
(4)
Therefore, from equations (4) and (5), the fuzzy eigenvalue $(\lambda_{m}^{0}, \lambda_{m}^{1}, \lambda_{m}^{u}, \lambda_{m}^{l})$ can be obtained.

**Step 5. Test of consistency of fuzzy pairwise comparison matrix**

Taking $\alpha$-cut for fuzzy pairwise comparison matrix $\overline{A}$ ($0 \leq \alpha \leq 1$), $\overline{A}^{\alpha}$ should have the maximum eigenvalue $\lambda_{m} = n$ if it meets the consistency requirement. Hence, the trapezoidal fuzzy number $\overline{\lambda_{m}}$ should be close to $n$. According to Hsu (1994), the fuzzy consistency index (FCI) is defined as follows.

$$\overline{FCI} = \frac{\overline{\lambda_{m}} - n}{n - 1} = (f_{1}, f_{2}, f_{3}, f_{4}) \quad (6)$$

By following the rules, the consistency of the pairwise comparison matrix can be judged.

1. If $f_{1} > 0.1$, then the pairwise comparison matrix cannot meet the consistency requirement.
2. If $f_{4} \leq 0.1$, then the pairwise comparison matrix can meet the consistency requirement.
3. If $f_{1} \leq 0.1 \leq f_{4}$, then the consistency can be judged by consistency degree (CD) as follows.

$$CD = \frac{0.1 - f_{1}}{f_{4} + f_{3} - f_{2} - f_{1}}, \text{ for } f_{1} \leq 0.1 \leq f_{2}$$

$$CD = \frac{0.2 - f_{1} - f_{2}}{f_{4} + f_{3} - f_{2} - f_{1}}, \text{ for } f_{2} \leq 0.1 \leq f_{4}$$

$$CD = 1 - \frac{f_{4} - 0.1}{f_{4} + f_{3} - f_{2} - f_{1}}, \text{ for } f_{3} \leq 0.1 \leq f_{4}$$

Hsu (1994) suggested that if the CD value was closer to 1, the greater the probability of the pairwise comparison matrix meeting the consistency requirement.

(2) Define the fuzzy consistency ratio (FCR) as follows.
Fuzzy Hierarchical Weight Analysis for Criteria of the Taiwan National Quality Award

\[ FCR = \frac{FCI}{R.I} = (r_1, r_2, r_3, r_4) \]  

Hsu (1994) has also suggested the following rules to determine the consistency of a pairwise comparison matrix.

1. If \( r_1 > 0.1 \), then the pairwise comparison matrix cannot meet the consistency requirement.

2. If \( r_3 \leq 0.1 \), then the pairwise comparison matrix can meet the consistency requirement.

3. If \( r_1 \leq 0.1 \leq r_3 \), then the consistency can be judged by consistency ratio degree (CRD) as follows.

\[
\text{CRD} = \frac{0.1 - r_1}{r_4 + r_3 - r_2 - r_1}, \text{ for } r_1 \leq 0.1 \leq r_2
\]  

\[
\text{CRD} = \frac{0.2 - r_1 - r_2}{r_4 + r_3 - r_2 - r_1}, \text{ for } r_2 \leq 0.1 \leq r_3
\]  

\[
\text{CRD} = 1 - \frac{r_4 - 0.1}{r_4 + r_3 - r_2 - r_1}, \text{ for } r_3 \leq 0.1 \leq r_4
\]

Again, if CRD value is closer to 1, the greater is the probability of the pairwise comparison matrix meeting consistency requirements. In this paper, there is no alternative selection involved, and only the reasonable range of weight is concerned. Therefore, it is not proposed to discuss the fuzzy consistency ratio of the hierarchy (FCRH) in any greater detail.

**Step 6. Determining fuzzy eigenweight vectors**

Because of the positive irreducible matrix of \( A_f^f \) and \( A_g^g \), the fuzzy eigenweight vectors \( x_f^g \) and \( x_g^g \) can be determined as follows (Buckley, 1990; Hsu, 1994).

Let \( \alpha = 0 \) and \( \alpha = 1 \), then equation (4) becomes

\[
\sum_{j=1}^{n} a_{ij}^0 x_{ij}^0 = \lambda_m^0 x_{ij}^0 \quad 1 \leq i \leq n
\]  

\[
\sum_{j=1}^{n} a_{ij}^1 x_{ij}^1 = \lambda_m^1 x_{ij}^1 \quad 1 \leq i \leq n
\]
\[
\sum_{j=1}^{n} a_{ji}^0 x_j^0 = \lambda_{m_j}^0 x_j^0 \quad 1 \leq i \leq n
\]  
(16)

\[
\sum_{j=1}^{n} a_{ji}^1 x_j^1 = \lambda_{m_j}^1 x_j^1 \quad 1 \leq i \leq n
\]  
(17)

and then solve equations (14), (15), (16), and (17) to obtain:

\[
x_j^0 = a_i \cdot x_{nl}^0 \quad 1 \leq i \leq n
\]  
(18)

\[
x_j^1 = b_i \cdot x_{nl}^1 \quad 1 \leq i \leq n
\]  
(19)

\[
x_j^0 = c_i \cdot x_{nu}^0 \quad 1 \leq i \leq n
\]  
(20)

\[
x_j^1 = d_i \cdot x_{nu}^1 \quad 1 \leq i \leq n
\]  
(21)

where \(a_i, b_i, c_i\) and \(d_i\) are constants. By linear property, we know that

\[
x_{ji}^a = y_i(\alpha) \cdot x_{nl}^a
\]  
(22)

\[
x_{iu}^a = z_i(\alpha) \cdot x_{nu}^a
\]  
(23)

where \(y_i(\alpha) = a_i + (b_i - a_i)\alpha\) and \(z_i(\alpha) = c_i + (d_i - c_i)\).

1. if \(b_i - a_i \geq 0\), then let \(x_{nl}^a = \alpha + 1\) for \(1 \leq i \leq n\).

2. if \(b_i - a_i < 0\), then let

\[
H_i(\alpha) = \frac{|y_i'(\alpha)|}{y_i(\alpha)} + 1
\]  
(24)

\[
x_{nl}^a = \exp\{\sum_{i=1}^{n-1} \int_0^a H_i(x)dx\}
\]  
(25)

and we obtained \(x_{nl}^0 < x_{nl}^1\) for \(1 \leq i \leq n\) because \(x_{nl}^a\) is a strictly increasing function of \(\alpha\).

3. if \(d_i - c_i \leq 0\), then let \(x_{nu}^a = p - \alpha\), \(p \geq 3\) for \(1 \leq i \leq n\).

4. if \(d_i - c_i > 0\), then let

\[
H_i(\alpha) = \frac{|z_i'(\alpha)|}{z_i(\alpha)} + 1
\]  
(26)

\[
x_{nu}^a = \exp\{\sum_{i=1}^{n-1} \int_0^a H_i(x)dx\}
\]  
(27)

and we obtained \(x_{nu}^1 < x_{nu}^0\) for \(1 \leq i \leq n\) because \(x_{nu}^a\) is a strictly decreasing function of \(\alpha\).

5. if \(x_{ji}^1 \leq x_{ju}^1\) for \(1 \leq i \leq n\), then let \(x_{ji}^0 = x_{j1}, x_{ji}^1 = x_{j2}, x_{ju}^1 = x_{j3}, x_{ju}^0 = x_{j4}\).
6. if \( x_{il} > x_{iu} \) for \( 1 \leq i \leq n \), then find \( k > 0 \) to make \( k \cdot x_{il} \leq x_{il} \) and let \( k \cdot x_{iu} = x_{il} \).

\[
k \cdot x_{il} = x_{i2}, \quad k \cdot x_{iu} = x_{i3}, \quad k \cdot x_{iu} = x_{i4}.
\]

From (5) and (6) above, the fuzzy eigenvector \( \bar{x}_{i} \) can be expressed as \( (x_{i1}, x_{i2}, x_{i3}, x_{i4}) \).

**Step 7. Normalization of fuzzy weight**

The crisp value of criteria weights should be less than or equal to 1, as should be the fuzzy weights. The above procedure cannot ensure the generation of fuzzy numbers that are all less than or equal to 1. Thus, they should be normalized.

\[
\bar{X} = \frac{1}{n} \sum_{i=1}^{n} \bar{x}_{i}, \quad \bar{X}_{i} = \bar{x}_{i} \cdot (\cdot) (\bar{X}^{*})^{-1}, \quad 1 \leq i \leq n
\]

where \( \bar{X} \) means the normalized fuzzy weight of criterion \( i \) at some level of hierarchy. So \( \bar{X}_{i} = (\bar{x}_{i1}, \bar{x}_{i2}, \bar{x}_{i3}, \bar{x}_{i4}) \). If \( \bar{x}_{i4} > 1 \) for \( 1 \leq i \leq n \), let \( x = \max \{ \bar{x}_{i4} \} \), and do the normalization again as follows to ensure fuzzy weight less than or equal 1.

\[
\bar{X}_{i}^{*} = \bar{X}_{i} \cdot (\cdot) (x)^{-1}
\]

where \( \bar{X}_{i}^{*} \) means the normalized fuzzy weight of criterion \( i \) at some level of hierarchy shifted to interval \([0,1]\).

**Step 8. Determining reasonable range of weight for each TNQA criterion**

Generally, we can take \( \alpha \)-cut, \( \alpha = 0.8 \), to find reasonable range of weight for each of these fuzzy numbers. However, to be more simple and precise, \( \alpha = 1 \) is taken. Therefore, the reasonable range of weight (RRW) for each TNQA criterion can be obtained.

**Implementation**

The implementation of FHWA for TNQA criteria is described by the following procedure (as described above).

**Developing an hierarchical structure for determining criteria weights of TNQA**

The present study focuses on determining the reasonable range of criteria weights of the TNQA from the perspective of committee members. Thus, first of all, an hierarchical structure for determining criteria weights of TNQA is established, as shown in Figure 1.
Constructing fuzzy comparison matrices

The Corporate Synergy Development Center (CSD) is in charge of the TNQA and has 43 TNQA committee members’ profiles for 2001 on hand. With the cooperation of the CSD, all 43 TNQA committee members were asked to fill in questionnaires by mail. Of these 43 requests, 32 surveys were returned. Using the questionnaires listed in Appendix A, each TNQA committee member answers were collected and translated by linguistic variables into either ‘crisp numbers’ or ‘intervals’ for each comparison between two criteria. Fuzzy pairwise comparison matrices among criteria were constructed for each TNQA committee member. Trapezoidal fuzzy numbers, $\tilde{1} - \tilde{9}$ were used to expressed the preference in the pairwise comparisons. One of the fuzzy comparison matrices of criteria made by a TNQA committee member is shown as an example below:

$$
\begin{array}{cccccccc}
\text{criteria} & \text{I} & \text{II} & \text{III} & \text{IV} & \text{V} & \text{VI} & \text{VII} \\
\text{I} & 1 & 5 & \tilde{5} & 5 & 3 & \frac{1}{7} & \tilde{1}/7 \\
\text{II} & \frac{1}{5} & 1 & 1 & 1 & \frac{1}{2} & \frac{1}{9} & \tilde{1}/2 \tilde{1}/9 \\
\text{III} & \frac{1}{5} & 1 & 1 & 1 & \frac{1}{3} & \frac{1}{7} & \tilde{1}/3 \tilde{1}/7 \\
\text{IV} & \frac{1}{5} & 1 & 1 & 5 & \frac{1}{7} & \frac{1}{9} & \tilde{1}/7 \tilde{1}/9 \\
\text{V} & \frac{1}{5} & 1 & 1 & \frac{1}{5} & 1 & \frac{1}{5} & \frac{1}{9} \\
\text{VI} & \frac{1}{3} & \tilde{2} & \frac{3}{7} & 5 & 1 & \frac{1}{7} & \tilde{1}/7 \tilde{1}/7 \\
\text{VII} & \tilde{7} & 9 & 7 & 9 & \tilde{9} & \tilde{7} & 1
\end{array}
$$

Screening non-qualified pairwise comparison matrices

To determine the CR value for each fuzzy comparison matrix, defuzzification was employed. In this paper, the defuzzified value is the average of four trapezoidal fuzzy numbers, $\alpha, \beta, \gamma,$ and $\delta$. As noted above, a $\text{CR} \leq 0.1$ was deemed to be acceptable. After performing the consistency ratio tests for 32 pairwise comparison matrices of criteria, 7 were deleted due to $\text{CR} \geq 0.1$, which means the conflict pairwise comparisons one after another and were therefore deemed to be nonqualified respondents.

Determining fuzzy maximum eigenvalue
In this paper, there were 25 qualified pairwise comparison matrices which involved fuzzy evaluation. Geometric means of 25 judgment values were taken, as suggested by Saaty (1980), as aggregated comparison matrices for this group decision problem. However, the aggregated matrix should be broken into four due to the trapezoidal fuzzy number involved. They are shown as follows.

$$A^0 = \begin{bmatrix}
1.000 & 2.068 & 1.502 & 2.166 & 2.213 & 2.240 & 0.471 \\
0.449 & 1.000 & 0.808 & 1.476 & 1.529 & 1.465 & 0.354 \\
0.632 & 1.080 & 1.000 & 1.738 & 1.442 & 1.521 & 0.455 \\
0.449 & 0.650 & 0.575 & 1.000 & 1.259 & 0.861 & 0.296 \\
0.397 & 0.599 & 0.622 & 0.682 & 1.000 & 0.755 & 0.347 \\
0.395 & 0.697 & 0.608 & 1.111 & 1.242 & 1.000 & 0.335 \\
1.803 & 2.562 & 2.094 & 3.333 & 2.787 & 2.758 & 1.000
\end{bmatrix}$$

$$A^1 = \begin{bmatrix}
1.000 & 2.118 & 1.522 & 2.221 & 2.285 & 2.337 & 0.475 \\
0.456 & 1.000 & 0.837 & 1.505 & 1.580 & 1.411 & 0.365 \\
0.640 & 1.120 & 1.000 & 1.738 & 1.527 & 1.562 & 0.461 \\
0.446 & 0.638 & 0.555 & 1.000 & 1.272 & 0.875 & 0.324 \\
0.411 & 0.608 & 0.635 & 0.689 & 1.000 & 0.772 & 0.350 \\
0.404 & 0.683 & 0.617 & 1.119 & 1.256 & 1.000 & 0.339 \\
2.072 & 2.615 & 2.119 & 3.346 & 2.809 & 2.809 & 1.000
\end{bmatrix}$$

$$A^1_u = \begin{bmatrix}
1.000 & 2.194 & 1.561 & 2.324 & 2.432 & 2.476 & 0.486 \\
0.473 & 1.000 & 0.892 & 1.557 & 1.646 & 1.464 & 0.382 \\
0.657 & 1.171 & 1.000 & 1.738 & 1.574 & 1.621 & 0.472 \\
0.467 & 0.742 & 0.654 & 1.000 & 1.298 & 0.893 & 0.299 \\
0.438 & 0.633 & 0.699 & 0.703 & 1.000 & 0.812 & 0.356 \\
0.428 & 0.695 & 0.627 & 1.142 & 1.295 & 1.000 & 0.349 \\
2.107 & 2.741 & 2.169 & 3.368 & 2.857 & 2.892 & 1.000
\end{bmatrix}$$

$$A^0_u = \begin{bmatrix}
1.000 & 2.226 & 1.581 & 2.375 & 2.517 & 2.500 & 0.487 \\
0.484 & 1.000 & 0.926 & 1.581 & 1.670 & 1.499 & 0.390 \\
0.665 & 1.237 & 1.000 & 1.738 & 1.607 & 1.645 & 0.477 \\
0.479 & 0.677 & 0.575 & 1.000 & 1.312 & 0.918 & 0.300 \\
0.452 & 0.654 & 0.693 & 0.711 & 1.000 & 0.805 & 0.359 \\
0.446 & 0.682 & 0.629 & 1.161 & 1.324 & 1.000 & 0.404 \\
1.845 & 2.828 & 2.195 & 3.378 & 2.883 & 2.928 & 1.000
\end{bmatrix}$$
was obtained as follows:

\[ A^0, A^1, A^n \text{ and } A_n^0 \text{ gave eigenvalues of } \lambda_{m^0} = 6.8366, \lambda_{m^1} = 6.956, \lambda_{m^n} = 7.175, \text{ and } \lambda_{m^n} = 7.2438 \text{ respectively.} \]

**Performing the test of consistency for fuzzy pairwise comparison matrix**

In this paper, by equation (6), the $\overline{FCI}$ was obtained as follows:

\[
\overline{FCI} = (-0.0272, -0.0073, 0.0292, 0.0406).
\]

By rule of $f_i \leq 0.1$ noted above, so we know that the pairwise comparison matrix can meet the consistency requirement. And again, by equation (10), the $\overline{FCR}$ was obtained as follows:

\[
\overline{FCR} = (-0.0206, -0.0055, 0.0221, 0.0308).
\]

Also, by rule $r_i \leq 0.1$ noted above, so we know that the pairwise comparison matrix can meet the consistency requirement.

**Determining fuzzy eigenweight vectors**

According to statements noted above, that is:

- if $x_{il}^0 \leq x_{iu}^1$ for $1 \leq i \leq n$, then let $x_{il}^0 = x_{i1}$, $x_{il}^1 = x_{i2}$, $x_{iu}^1 = x_{i3}$, $x_{iu}^0 = x_{i4}$.

- if $x_{il}^0 > x_{iu}^1$ for $1 \leq i \leq n$, then find $k > 0$ to make $k \cdot x_{il}^1 \leq x_{iu}^1$ and let $k \cdot x_{il}^0 = x_{i1}$, $k \cdot x_{il}^1 = x_{i2}$, $k \cdot x_{iu}^1 = x_{i3}$, $k \cdot x_{iu}^0 = x_{i4}$.

the fuzzy eigenvector $\tilde{x}_i$ can be expressed as $(x_{i1}, x_{i2}, x_{i3}, x_{i4})$. In this paper, according to previous equations (18), (19), (20), and (21), fuzzy eigenweight vectors can be determined as follows:

\[
\begin{align*}
x_{i1}^0 &= 0.676 \cdot x_{i1}^0 & x_{i1}^1 &= 0.667 \cdot x_{i1}^1 & x_{i2}^0 &= 0.700 \cdot x_{i2}^0 & x_{i2}^1 &= 0.677 \cdot x_{i2}^1 \\
x_{i3}^0 &= 0.402 \cdot x_{i3}^0 & x_{i3}^1 &= 0.393 \cdot x_{i3}^1 & x_{i4}^0 &= 0.414 \cdot x_{i4}^0 & x_{i4}^1 &= 0.399 \cdot x_{i4}^1 \\
x_{i1}^0 &= 0.463 \cdot x_{i1}^0 & x_{i1}^1 &= 0.456 \cdot x_{i1}^1 & x_{i2}^0 &= 0.472 \cdot x_{i2}^0 & x_{i2}^1 &= 0.457 \cdot x_{i2}^1 \\
x_{i3}^0 &= 0.298 \cdot x_{i3}^0 & x_{i3}^1 &= 0.291 \cdot x_{i3}^1 & x_{i4}^0 &= 0.297 \cdot x_{i4}^0 & x_{i4}^1 &= 0.297 \cdot x_{i4}^1 \\
x_{i1}^0 &= 0.272 \cdot x_{i1}^0 & x_{i1}^1 &= 0.267 \cdot x_{i1}^1 & x_{i2}^0 &= 0.279 \cdot x_{i2}^0 & x_{i2}^1 &= 0.270 \cdot x_{i2}^1 \\
x_{i3}^0 &= 0.314 \cdot x_{i3}^0 & x_{i3}^1 &= 0.305 \cdot x_{i3}^1 & x_{i4}^0 &= 0.322 \cdot x_{i4}^0 & x_{i4}^1 &= 0.306 \cdot x_{i4}^1
\end{align*}
\]

We found that each criterion satisfied $b_i - a_i < 0$ and $d_i - c_i \leq 0$. Hence, we can obtain a fuzzy weight for each criterion as follows:
The normalization for fuzzy weights

After the normalization, the fuzzy weights for the TNQA criteria are as follows.

\[ x_1 = (0.0907, 0.1107, 0.3545, 0.6131) \]
\[ x_2 = (0.0539, 0.0652, 0.2089, 0.3626) \]
\[ x_3 = (0.0621, 0.0756, 0.2393, 0.4134) \]
\[ x_4 = (0.0400, 0.0483, 0.1555, 0.2601) \]
\[ x_5 = (0.0365, 0.0443, 0.1414, 0.2444) \]
\[ x_6 = (0.0421, 0.0506, 0.1603, 0.2820) \]
\[ x_7 = (0.1342, 0.1659, 0.5237, 0.8759) \]

Determination of reasonable range of criterion weight

The reasonable range of weight (RRW) for each TNQA criterion in contrast to the current weight is listed in Table 3. From Table 3, we see that all original weights of TNQA are within the RRW. Therefore, the current distribution of weights of the TNQA are acceptable.

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<th>Criterion</th>
<th>Current weight</th>
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<tr>
<td>I. Leadership</td>
<td>0.15</td>
<td>0.1107~ 0.3545</td>
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<tr>
<td>II. Innovation and Strategic Management</td>
<td>0.11</td>
<td>0.0652~ 0.2089</td>
</tr>
<tr>
<td>III. Customer/Market Development</td>
<td>0.11</td>
<td>0.0756~ 0.2393</td>
</tr>
<tr>
<td>IV. Human Resource and Knowledge Management</td>
<td>0.11</td>
<td>0.0483~ 0.1555</td>
</tr>
<tr>
<td>V. Information Management</td>
<td>0.11</td>
<td>0.0443~ 0.1414</td>
</tr>
<tr>
<td>VI. Process Management</td>
<td>0.11</td>
<td>0.0506~ 0.1603</td>
</tr>
<tr>
<td>VII. Business Result</td>
<td>0.30</td>
<td>0.1659~ 0.5237</td>
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Discussion

In general, the more complicated are the problems, the more likely it is that fuzzy judgments or comparisons are required for group decision-making. In the pairwise comparisons of AHP, trapezoidal fuzzy numbers are introduced to improve the scaling scheme of Saaty method. Each TNQA committee member was allowed to express an indefinite opinion by assigning an ‘interval’ when making a comparison between two criteria. The present study noted the responses from TNQA committee members and observed that many of the pairwise comparisons between two criteria were answered with an ‘interval’ response. This was in accordance with expectations prior to the study. After FHWA, RRW was obtained for each TNQA criterion, as shown in Table 3. It was found that the criteria were actually adjustable within a reasonable range in response to necessary changes in accordance with global or domestic economic requirements. The present study does not criticize the current TNQA criteria weights on the basis of whether they are the best design for a ‘game rule’. However, the study has provided an evaluation procedure that can be used as a baseline for the making of TNQA criteria, or for the revising of the criteria, no matter how TNQA committee members decide the criteria weights. The evaluation procedure should be used before making or revising criteria weights in future, or before a complete change in the whole framework of the TNQA.

In addition, the present study found that some committee members assigned extreme numbers when making a comparison of relative importance among criteria. This demonstrated their strongly subjective consciousness in making certain judgments. For this reason the present study used the geometrical average to represent group opinions. In doing so, data skewed by extreme value were avoided.

Another interesting aspect was the backgrounds of the various TNQA committee members. The committee members in 2001 were basically from four different groups. Of all TNQA members, 41.9% were from academia, 27.9% from government sectors, 13.9% from semi-official organizations, and only 16.3% from private businesses. This distribution is perhaps not ideal. The TNQA is an excellent quality system that is mainly designed for private businesses. It provides an excellent paradigm for companies that have excellent quality performance. However, the Wallace Company, a winner of the MBNQA in 1990, went bankrupt (Hill, 1993). Florida Power and Light won the prestigious Deming Prize only to see a rise in cost and a dismantling of the TQM program (Wiesemdanger, 1993). Against this background, it is worthwhile rethinking the whole concept of excellent quality performance. It should be possible to make a TNQA winner link quality and profit together more closely. The
involvement of more voices and opinions from private business would be helpful in this regard in undertaking any fundamental reappraisal of TNQA criteria.

**Conclusion**

The TNQA has been successfully conducted for thirteen years since it was established in 1990. So far, the process of weighting the criteria of the TNQA has not been explored. In fact, it is not known how TNQA committee members first created the weightings for each criterion. However, the present study can verify that the weightings of the criteria are reasonable, as a result of analyzing the opinions of committee members through FHWA. In this paper, trapezoidal fuzzy numbers were adopted to measure the relative importance of criteria from the perspective of various committee members. Each committee member was allowed to choose linguistic variables using ‘interval’ expressions that reflected his or her subjective judgments of the relative importance of criteria. This is very close to meeting the reality of group decision-making. After the evaluation of FHWA, a reasonable range of weight for each criterion was obtained. The results showed that the current distribution of criteria weights of the TNQA are all within a reasonable range.

In this paper, trapezoidal fuzzy numbers were introduced into the conventional AHP to improve imprecise judgments among TNQA criteria. There are two advantages in using FHWA for determining RRWs of the TNQA.

1. Fuzzy numbers can extend the range of a crisp comparison matrix of the AHP method. Adoption of fuzzy numbers can make the decision-making closer to reality in terms of real human decision-making.

2. Basically, the FHWA procedure is almost the same as the conventional AHP method. The only difference is the fuzzy numbers involved in pairwise comparison matrices among TNQA criteria. Some modifications were made to conventional AHP due to the fuzzy concept involved. FHWA is as useful and easy to understand as the AHP method.

There are two suggestions for future study with regard to the TNQA. First, in this study, after the test of consistency only 25 qualified respondents’ pairwise comparisons matrices were collected and analyzed through FHWA. This sample size may be a little small to make conclusive findings from the analysis. To obtain more opinions from quality experts, the
questionnaire respondents could include past and current TNQA committee members. Quality experts in private business could also be on the invitation list when seeking opinions. Secondly, the TNQA has now become a model of excellence in business performance in Taiwan. An increasing number of non-manufacturing organizations compete for the TNQA to increase their organizational efficiency. Therefore, the weights of TNQA criteria should be independently designed or modified to allow for the requirements and needs of different businesses.

**References**


APPENDIX A: Questionnaire scale items

Please indicate your level of importance with a single ‘number’ or ‘interval’ in each following comparison between two criteria:

Scale Anchors: Equal Importance (1), Weak Importance (3), Essential Importance (5), Very Strong Importance (7), Absolute Importance (5), Intermediate Values (2, 4, 6, 8).

| Scale | Criterion | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|-----------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I     |           |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| II    |           |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| III   |           |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| IV    |           |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| V     |           |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| VI    |           |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| VII   |           |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

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Fuzzy Hierarchical Weight Analysis for Criteria of the Taiwan National Quality Award

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