Application of a Fuzzy Analytic Hierarchy Process to Technical Economic Evaluation

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Abstract — Fuzzy analytic hierarchy process is used to determine the index weight and then multi-level fuzzy comprehensive evaluation method is used for actual evaluation of some building in China. According to the building energy efficiency standards and the domestic and foreign related research literature sources, an evaluation system for energy-saving buildings is established. It is anticipated that this study will help promote the development of technical economic assessment research and the building energy-saving industry in China. The proposed model and the algorithm provide a tool for conducting technical economic assessment of energy-saving technology and optimizing energy saving design schemes. It will be useful to policy makers and decision makers in China.

Keywords — technical economic; fuzzy analytic hierarchy process; energy-saving.

I. INTRODUCTION

China is experiencing a rapid economic development process in recent decades, while it also brings the problem of energy consumption growing quickly and continuously [1]. The construction industry as a pillar industry of China's national economy, both new building and the existing building are the high resource and energy consumption fields [2].

The evaluation index system should be an integrated hierarchical system. Evaluation index of subsystem is not completely independent, but there is a certain degree of correlation and mutual restriction [3,4]. Indicators reflect all aspects of the architectural energy saving effect, it also can reflect the relationship between these aspects. Energy-efficient building itself contains the content of the multilayer, therefore the evaluation index system should also reflect the corresponding hierarchy multiplicity, making the evaluation index system as a relatively comprehensive whole [5].

The evaluation index system must follow the objective laws of science[6]. Indicators should be short and concise, evaluation calculation method is simple and the evaluation system is not too complex [7]. Under the premise of the accuracy of the evaluation results, some indexes with tiny influence on the result are removed. Index data should be easy to collect. Economic or time cost is very high to get some indexes. Some indexes influence the final result, but it is very difficult to get under the general conditions. These indicators are not listed into the system. Referencing to domestic and international literature about evaluation system of building energy-saving, based on the principles of evaluation index system, the energy-saving comprehensive evaluation index system of residential building of some city in China is built after repeatedly selecting of the index. Multi-level fuzzy comprehensive evaluation method is used for analysis of some building. The result shows that the energy-saving technology of residential buildings can help buildings get a better energy-saving effect.

In the next section, the determination of indicators is investigated. In Section 3, fuzzy analytic hierarchy process is used for technical economic evaluation. In section 4, empirical analysis is given. Finally, this paper summarizes the research.

II. THE DETERMINATION OF INDICATORS

According to the building energy efficiency standards and the domestic and foreign related research literature sources[8-10], preliminary evaluation system is established, which is shown in table 1.

<table>
<thead>
<tr>
<th>No</th>
<th>Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>building towards</td>
</tr>
<tr>
<td>2</td>
<td>shape coefficient</td>
</tr>
<tr>
<td>3</td>
<td>window wall proportion</td>
</tr>
<tr>
<td>4</td>
<td>green construction</td>
</tr>
<tr>
<td>5</td>
<td>building materials recycled use</td>
</tr>
<tr>
<td>6</td>
<td>residents' awareness of energy saving</td>
</tr>
<tr>
<td>7</td>
<td>outer wall heat transfer coefficient</td>
</tr>
<tr>
<td>8</td>
<td>heat transfer coefficient of the roof</td>
</tr>
<tr>
<td>9</td>
<td>Roof thermal inertia index</td>
</tr>
<tr>
<td>10</td>
<td>air tightness</td>
</tr>
<tr>
<td>11</td>
<td>External wall thermal inertia index</td>
</tr>
<tr>
<td>12</td>
<td>heat transfer coefficient of outside window</td>
</tr>
<tr>
<td>13</td>
<td>Window shading coefficient</td>
</tr>
<tr>
<td>14</td>
<td>Air conditioning and lighting power consumption</td>
</tr>
<tr>
<td>15</td>
<td>Renewable energy sources utilization</td>
</tr>
<tr>
<td>16</td>
<td>CO2 emissions</td>
</tr>
</tbody>
</table>

TABLE 1. PRELIMINARY EVALUATION SYSTEM
In the process for further screening the indicators, some indicators do not have operability. Green construction and building materials recycling is not suitable for the evaluation of existing buildings. Residents’ energy saving consciousness is difficult to determine its advantages and disadvantages. CO2 emissions can not be calculated perfectly under the condition of existing technology. Based on the above ideas and principles, the evaluation index is divided into three types of design parameters, coefficient of heat preservation and heat insulation coefficient, finally the determined index structure is shown in table 2. The target layer is A.

### III. FUZZY ANALYTIC HIERARCHY PROCESS

Analytic hierarchy process (AHP) is a kind of multi-objective decision analysis method. Supposing there are \( n \) number of objects, \( A_1, A_2, \ldots, A_n \) and the weight of them is \( w_1, w_2, \ldots, w_n \).

\[
A = \begin{bmatrix}
w_1 / w_1 & w_1 / w_2 & \ldots & w_1 / w_n \\
w_2 / w_1 & w_2 / w_2 & \ldots & w_2 / w_n \\
\vdots & \vdots & \ddots & \vdots \\
w_n / w_1 & w_n / w_2 & \ldots & w_n / w_n 
\end{bmatrix}
\]

The target layer is A, rule layer is C and measure layer is P. The two compared two judgment matrix for A-C is calculated and judgment matrix for Ci-P is calculated. Then the two compared two judgment matrix for A-C is determined index structure is shown in table 2. The target layer is A.

<table>
<thead>
<tr>
<th>Rule layer</th>
<th>Index layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>design parameter B1</td>
<td>building towards C1</td>
</tr>
<tr>
<td></td>
<td>shape coefficient C2</td>
</tr>
<tr>
<td></td>
<td>window wall proportion C3</td>
</tr>
<tr>
<td>heat preservation coefficient B2</td>
<td>outer wall heat transfer coefficient C4</td>
</tr>
<tr>
<td></td>
<td>heat transfer coefficient of the roof C5</td>
</tr>
<tr>
<td></td>
<td>heat transfer coefficient of window C6</td>
</tr>
<tr>
<td></td>
<td>air tightness C7</td>
</tr>
<tr>
<td>heat insulation coefficient B3</td>
<td>External wall thermal inertia index C8</td>
</tr>
<tr>
<td></td>
<td>Roof thermal inertia index C9</td>
</tr>
<tr>
<td></td>
<td>Window shading coefficient C10</td>
</tr>
</tbody>
</table>

#### TABLE 2. THE COMPREHENSIVE EVALUATION INDEX SYSTEM

Relative weights of rule layer A to measure layer C is calculated and test its consistency. When relative weights of the various levels of the factors are obtained, combination weight calculation of measures layer is calculated. Relative weights of target layer A to rule layer C is

\[
\overline{w}_i = \left( w_{i1}^{(1)}, w_{i2}^{(1)}, \ldots, w_{in}^{(1)} \right)^T
\]

Relative weights of rule layer A to measure layer C is

\[
\overline{w}_l = \left( w_{l1}^{(2)}, w_{l2}^{(2)}, \ldots, w_{ln}^{(2)} \right)^T, \quad l = 1, 2, \ldots, k.
\]

Determine the evaluation factor set. The fuzzy evaluation is described as follows.

1. Evaluation factors domain \( U \) can be divided into \( s \) number of mutually disjoint subsets according to the different attributes.

\[
U = \{ U_1, U_2, \ldots, U_s \}
\]

\[
U_k = \{ u_{k1}, u_{k2}, \ldots, u_{ks} \}, \quad k = 1, 2, \ldots, s.
\]

2. Calculate the weight of each evaluation factor in \( U_k \).

\[
A_k = \{ a_{k1}, a_{k2}, \ldots, a_{ks} \}
\]

3. Determine evaluation set

\[
V = (v_1, v_2, \ldots, v_n)
\]

4. Carry out single factor judgment for each factor of \( U_k \), then fuzzy relation matrix is

\[
R_k = \begin{bmatrix}
r_{k11} & r_{k12} & \cdots & r_{k1m} \\
r_{k21} & r_{k22} & \cdots & r_{k2m} \\
\vdots & \vdots & \ddots & \vdots \\
r_{km1} & r_{km2} & \cdots & r_{kmn}
\end{bmatrix}
\]

\( r_{kj} \) represents the degree of object be evaluated to \( v_j \). That is the degree of \( u_{k1} \) belonging to \( v_j \).

5. Carry out the first level fuzzy comprehensive evaluation.

\[
B_k = \prod_{j=1}^{n} a_{kj} \circ v_j
\]

6. Carry out the second level fuzzy comprehensive evaluation.

\[
U_k \text{ is taken as } s \text{ number of single factor, the weight of each factor of } U \text{ is } A = (a_1, a_2, \ldots, a_n).
\]

The second level fuzzy relationship matrix is

\[
\overline{w}_i = \left( w_{i1}^{(1)}, w_{i2}^{(1)}, \ldots, w_{in}^{(1)} \right)^T
\]

(\( \overline{w}_i \)) is the i-th element of vector \( Aw \). Judging matrix consistency index is calculated and test its consistency.

\[
\lambda_{\text{max}} = \sum_{i=1}^{n} \frac{(\overline{Aw}_i)}{n}
\]

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In order to get the weight of each evaluation index, the structure table of the evaluation index system is made into questionnaire. We invite 20 number of related construction energy conservation experts from architectural design institute, real estate consulting, real estate developers and construction science research. Opinions are put forward. Finally 1-9 scale judgment matrix is constructed. Judgment matrix of criteria layer index is shown in table 3(a).

\[
R = \begin{bmatrix}
    b_{11} & b_{12} & \ldots & b_{1m} \\
    b_{21} & b_{22} & \ldots & b_{2m} \\
    \vdots & \vdots & \ddots & \vdots \\
    b_{n1} & b_{n2} & \ldots & b_{nm}
\end{bmatrix},
\]

\[b_i \text{ represents the degree of } U_i \text{ belonging to } v_j, \]

\[B = A \cdot R = (b_{1}, b_{2}, \ldots, b_{n}).\]

\[
W_i = (0.389, 0.333, 0.278)^T, \quad \lambda_{max} = 3.003.
\]

\[
CI = (3.003 - 3) / (3 - 1) = 0.0015, \quad RI = 0.58.
\]

\[
CR = 0.0015 / 0.58 < 0.1.
\]

It passes consistency check, meaning the above \( W_i \) can be taken as weight vector. Judgment matrix of criteria layer index to index layer is shown in table 3(b).

\[
W_{ij} = (0.389, 0.278, 0.333)^T, \quad \lambda_{max} = 3.003.
\]

\[
CI = (3.003 - 3) / (3 - 1) = 0.0015, \quad RI = 0.58.
\]

\[
CR = 0.0015 / 0.58 = 0.0026 < 0.1.
\]

It passes consistency check, meaning the above \( W_{ij} \) can be taken as weight vector. Judgment matrix of index layer to rule layer is shown in table 3(c).

\[
W_{b1} = (0.273, 0.273, 0.227, 0.227)^T, \quad \lambda_{max} = 4.004.
\]

\[
CI = (4.004 - 4) / (4 - 1) = 0.0013, \quad RI = 0.58.
\]

\[
CR = 0.0013 / 0.58 = 0.0032 < 0.1.
\]

It passes consistency check, meaning the above \( W_{b1} \) can be taken as weight vector. Judgment matrix of index layer to criterion layer is shown in figure 4.
Table 6. Membership of evaluation level of each index

<table>
<thead>
<tr>
<th>index</th>
<th>very good</th>
<th>better</th>
<th>general</th>
<th>worse</th>
</tr>
</thead>
<tbody>
<tr>
<td>building towards</td>
<td>0.75</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>shape coefficient</td>
<td>0.15</td>
<td>0.2</td>
<td>0.65</td>
<td>0</td>
</tr>
<tr>
<td>window wall proportion</td>
<td>0.4</td>
<td>0.5</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>outer wall heat transfer coefficient</td>
<td>0</td>
<td>0.3</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>heat transfer coefficient of the roof</td>
<td>0.25</td>
<td>0.65</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>heat transfer coefficient of window</td>
<td>0.05</td>
<td>0.45</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>air tightness</td>
<td>0.2</td>
<td>0.55</td>
<td>0.25</td>
<td>0</td>
</tr>
<tr>
<td>external wall thermal inertia index</td>
<td>0.3</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>roof thermal inertia index</td>
<td>0.4</td>
<td>0.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>window shading coefficient</td>
<td>0.2</td>
<td>0.65</td>
<td>0.15</td>
<td>0</td>
</tr>
</tbody>
</table>

Evaluation matrix of each index is

\[
R_1 = \begin{bmatrix}
0.75 & 0.25 & 0 & 0 \\
0.15 & 0.2 & 0.65 & 0 \\
0.4 & 0.5 & 0.1 & 0 \\
0 & 0.3 & 0.6 & 0.1 \\
0.25 & 0.65 & 0.1 & 0 \\
0.05 & 0.45 & 0.5 & 0 \\
0.2 & 0.55 & 0.25 & 0 \\
0.3 & 0.7 & 0 & 0 \\
0.4 & 0.6 & 0 & 0 \\
0.2 & 0.65 & 0.15 & 0 \\
\end{bmatrix}
\]

The single factor evaluation matrix is

\[
W_i = W_{n} \circ R_i = (0.389, 0.278, 0.333) \circ R_1
\]

Evaluation level: very good(5-4.6), better(4.5-3.6), general(3.5-2.6), worse(2.5-2).

\[
G = \frac{\sum_{i=1}^{n} P_i q_i}{\sum_{i=1}^{n} P_i} = 4.227
\]

The evaluation score of this project is 4.227, which belongs to the better level. Criterion layer index design parameter is 0.389, which is the maximum weight of the first level index. Among them, index weight of the orientation, shape coefficient and window wall construction are respectively 0.273, 0.273, 0.227 and 0.227. Single factor evaluation matrix of heat preservation is \( R = (0.125, 0.487, 0.361, 0.027) \). 12.5% of people think that it is very good; 48.7% of people think it is better; 36.1% of people think that it is general. In accordance with the principle of maximum membership degree, the overall design parameters belong to the level of very good.

Heat preservation coefficient has the highest weight of the first level index. Among them, weights of the outer wall heat transfer coefficient, the roof heat transfer coefficient, window heat transfer coefficient, window air tightness are respectively 0.273, 0.273, 0.227 and 0.227. Single factor evaluation matrix of heat preservation is \( R = (0.125, 0.487, 0.361, 0.027) \). 12.5% of people think that it is very good; 48.7% of people think it is better; 36.1% of people think that it is general. In accordance with the principle of maximum membership degree, the overall score is 4.227, indicating the project energy saving is in the average level and most of the indicators evaluation results are more average.

V. Conclusions

It is the curial time of our country construction energy conservation work. With the development of China energy-saving building, it also brings several problems: low industrialized energy-saving building, low integration in set technology, low labor productivity and high resources consumption. The main purpose of this study is to establish an analytical approach including mathematical model and its corresponding algorithm for technical economic assessment of energy saving technologies applied in residential buildings. A theoretical basis and support for government
departments to develop energy-saving measures and policy is provided for reference in theory.

REFERENCES


