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Application of the Grey Fuzzy Comprehensive Evaluation Method in Energy Saving Evaluation of Large-scale Public Buildings

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Abstract: In order to comprehensively evaluate the energy-saving effects of large-scale public building in hot summer and warm winter area, the Fuzzy Comprehensive Evaluation Model (FCEM) for the energy-saving of public building is established from the aspects of construction design, building enclosure, building equipment, operation management and the use of comfort which is based on the basic principle of fuzzy mathematics from the viewpoint of total life cycle. Using this model to evaluate the energy-saving of large-scale public building in Xiamen city, then the evaluation grade of this area's energy-saving can be assessed for "Good" which can provide a reference for the energy-saving evaluation of public building.

Key words: Public building, energy-saving, fuzzy comprehensive evaluation, index system, whole life cycle

INTRODUCTION

Energy-saving and emission reduction has already become a focus and there are more and more studies related to the energy saving evaluation. The country's12th "Five-year Plan" shows a energy-saving target of 16% reduction in per unit GDP energy consumption by 2015 (The State Council of PRC, 2013). Up to now, building energy consumption has accounted for 30% of the total energy consumption in China. Among various kinds of enclosed structure, doors, windows, walls and roofs are the major parts of building energy consumption in hot summer and warm winter area with hot and damp weather. Doors and windows' energy consumption in multi-story building accounts for 50% of used energy consumption (Tao, 2009) and external walls' energy consumption accounts for 24% (Ma and Niu, 2011). Monolayer roof's energy consumption accounts for 50% of used energy consumption and Multi-layered roof energy consumption accounts for 8-10% (Li and Gao, 2013). Heating, Ventilation and Air Conditioning (HVAC) system's energy consumption accounts for 50-60% of annual energy consumption and the lighting system accounts for 20-30% while the heat transfer energy of college building enclosure accounts for 40-50% of HVAC system (Zhang and Xu, 2012). With the improvement of people's life quality and living comfort requirement, the proportion of building energy consumption will keep rising.

The existed building energy efficiency standards mainly concentrate on some comprehensive index and auxiliary index, such as heat consumption of building and the index of building enclosure's thermal performance. There are more and more studies related to the energy saving evaluation. Scholars from home and abroad have carried on the comprehensive evaluation research. Jin *et al*. (2011), Zhang and Wei (2011) and Jiang and Yang (2009) study about fuzzy comprehensive evaluation of rural house. Peng (2012) aimed at the evaluation index system of energy-saving for civilian construction, Jiang *et al*. (2012) put forward the evaluation index of public building in hot summer and cold winter area and the evaluation index system of residential building's energy-saving design in cold region is studied by Liu *et al.* (2013). A model (Xiao *et al*., 2012; Zhang and Xu, 2012) is established to evaluate the energy-saving effects of civilian construction and public construction, respectively in hot summer and cold winter area. For the particularity of region, existed research findings cannot be used in hot summer and warm winter area directly. The application of public building's energy-saving measures has been up to 100% basically in Xiamen City and the incremental cost percentage caused by energy-saving measures also shows a decreasing trend (Li and Gao, 2013). Building energy-saving effect cannot be assessed by an index or a stage. It should be taken into full account by the total life cycle of building's planning, design, producing, marketing, operating, using,

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maintenance and recycling (Zhou *et al*., 2013). This article adopts the method of fuzzy compressive evaluation to establish the building energy-saving evaluation model of public buildings in total life cycle in hot summer and warm winter area. It also comprehensively evaluates the existed energy-saving effect of public building.

ESTABLISHMENT OF FUZZY COMPREHENSIVE EVALUATION MODEL (FCEM)

The fuzzy comprehensive evaluation method is a comprehensive bid-evaluation method which is based on fuzzy mathematics. In accordance with the membership degree theory of fuzzy mathematics, qualitative evaluation can be turned into quantitative evaluation with fuzzy comprehensive evaluation method which generally evaluates the things or objects that are limited by various factors through the fuzzy mathematics (Song *et al*., 1996; Yuan *et al*., 2004; Yang *et al*., 2011). In a complex system, it is needed to take many factors which have different hierarchical relationships into consideration. With a great many of fuzzy phenomena and fuzzy concept in an evaluation, it's difficult to get the right evaluation result by using of the one level FCEM. In this case, the evaluation factors should fall into several categories by some property and then comprehensively evaluate every kind of evaluation results in a high level as well as every category. So, multilevel fuzzy comprehensive evaluation problems are brought forth. The steps of the evaluation are as follow:

Determine the factor discourse domain of evaluation objects: Factor set U can be divided as follows:

$$U = \{U_1, U_2, \cdots, U_N\}$$

In this formula: $U_i = \{U_1^{(i)}, U_2^{(i)}, \cdots, U_k^{(i)},\}$, i = 1, 2,···, N, that is to say, U_i contains k_i factors:

$$\sum_{i=1}^{N} k_i = n$$

besides, they also satisfy the following condition:

$$\bigcup_{i=1}^{N} U_i = U$$

The $U = \{U_1, U_2, \cdots, U_N\}$ can be named as first level factor set and $U_i = \{U_1^{(i)}, U_2^{(i)}, \cdots, U_k^{(i)},\}$ can be named as second level factor set.

Determine the evaluation set: Setting the evaluation set $V = \{V_1, V_2 \cdots, V_m\}$ and each level can be equivalent to a fuzzy subset.

Establish the fuzzy relation matrix: After structuring the hierarchical fuzzy subset, single factor index $u_j^{(i)}$ (i = 1, 2,···, 12) should be quantified one by one, that is, the membership degree of hierarchical fuzzy subset $(R|u_j^{(i)})$ is defined based on single factor and then fuzzy relation matrix is received:

$$R = \begin{bmatrix} R| & u_1^{(i)} \\ R| & u_2^{(i)} \\ & \cdots \\ R| & u_p^{(i)} \end{bmatrix} = \begin{bmatrix} r_{11}^{(i)} & r_{12}^{(i)} & \cdots & r_{1m}^{(i)} \\ r_{21}^{(i)} & r_{22}^{(i)} & \cdots & r_{2m}^{(i)} \\ \cdots & \cdots & \cdots & \cdots \\ r_{p1}^{(i)} & r_{p2}^{(i)} & \cdots & r_{pm}^{(i)} \end{bmatrix}_{p\times m}$$

The method to determine fuzzy mapping is using expert grading method to determine the evaluation result of single factor. Supposing that there are k panel members and those experts score u_i who is to be elected as v_j for c_{ij1}, $c_{ij2}, \cdots$, c_{ijk}, respectively, among which $0 \le c_{ijp} \le 100$, (p = 1, 2···, k; i = 1, 2,···,n; j = 1, 2,···, m) and:

$$r_{ij}' = \frac{c_{ij1} + c_{ij2} + \ldots + c_{ijk}}{k}$$

then normalization processing is carried out:

$$r_{ij} = \frac{r_{ij}'}{r_{i1}' + r_{i2}' + \ldots + r_{im}'} \tag{1}$$

In this formula, r_{ij} is the membership degree of u_i to v_j.

Determine the weights of evaluation factors: Determine the weight vector of evaluation factor in fuzzy comprehensive evaluation: $W = (w_1, w_2, \cdots, w_p)$. Factor w_i in weight vector W is the membership degree from factor u_i to fuzzy subset in nature:

$$\sum_{i=1}^{p} w_i = 1$$

$w_i \ge 0$, i = 1, 2,···, n. Weight is the key to comprehensive evaluation and it is determined by analytical hierarchy process generally.

Synthesize the results of fuzzy comprehensive evaluation: Vector B resulted from fuzzy comprehensive evaluation is based on the synthesis of weight vector matrix Wand fuzzy relation matrix R, that is:

$$W \circ R = (w_1, w_2, \cdots, w_p) \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{p1} & r_{p2} & \cdots & r_{pm} \end{bmatrix} = (b_1, b_2, \cdots, b_m) = B \tag{2}$$

In this formula, "∘" can be chosen to be (∧, ∨) or (•,+).

Processing of fuzzy comprehensive evaluation results: As fuzzy comprehensive evaluation set B is the fuzzy subset within comment set V, it is often named as comprehensive evaluation result in application and it also determines the final satisfied solution. Use the mean of maximum method that takes the factor ν in V which is the nearest to $\max_{1\le j\le m} b_j$ as evaluation result. That is:

$$\nu = \{\nu_j | \nu_j \rightarrow \max(b_i)\} \quad (3)$$

CASE ANALYSIS

Taking 45 large-scare public building in Xiamen City for example which with the floor area of more than 10000 m^2 for each building and a total construction building area of 1,300,000 m^2. The example buildings cover the three types of office building, hotel building and business building. Then according to the actual situation of the buildings, the energy efficiency is evaluated by using of multilevel FCEM as following:

Structure the evaluation index system and weight allocation: By comprehensive analysis of the factors affecting the building energy consumption: architectural design, envelope thermal performance, construction equipment, construction operation and management of energy efficiency and comfort and health, The Weight determined by the importance of influencing factors. Then, the fuzzy comprehensive evaluation model is established which with three levels of the macro, meso and micro as shows in Table 1.

Determine the comment set: Based on the actual requirement of evaluation, evaluation grade standard falls into four grades: excellent, good, qualified and unqualified. So the comment set is: $V = \{V_1, V_2, V_3, V_4\}$ = {excellent, good, qualified, unqualified}.

Each single factor's evaluation: Invite energy-efficient construction experts and scholars to form a judgment group, score each factor in Table1 through grading or voting, find its average value, then normalize the factor, so the single evaluation result of this area's building energy efficiency is received. Similarly, the evaluation result of each factor in the table can be received, see Table1.

Multilevel fuzzy comprehensive evaluation: To comprehensively evaluate this area's building energy efficiency by the multilevel fuzzy comprehensive evaluation method and Eq. 2. Based on the evaluation set, the fuzzy matrix of this area's building energy efficiency can be received:

$$R_1 = \begin{bmatrix} 0.26 & 0.36 & 0.24 & 0.14 \\ 0.35 & 0.44 & 0.16 & 0.05 \\ 0.34 & 0.26 & 0.34 & 0.06 \\ 0.24 & 0.31 & 0.27 & 0.18 \end{bmatrix}$$

The weight coefficient is A_1 = (0.420, 0.253, 0.216, 2.111), so this area's comprehensive evaluation is: $B_1 = A_1 \circ R_1$ = (0.298, 0.353, 0.245, 0.104). The operator in Eq. 2 adopts (•, +) because it not only deals with the

Table 1: Evaluation index of building energy efficiency and evaluation result of single factor

First level evaluation index and weight	Second level evaluation index and weight		Evaluation result of single factor: Excellent	Good	Qualified	Unqualified
Architectural design U_1						
0.19	Building orientation	0.420	0.26	0.36	0.24	0.14
	Shape coefficient	0.253	0.35	0.44	0.16	0.05
	Outdoor environment	0.216	0.33	0.26	0.34	0.06
	area ratio of window to wall	0.111	0.24	0.31	0.27	0.18
Thermal performance of building enclosure						
0.2	Thermal insulation properties of enclosure	0.550	0.62	0.17	0.21	0.00
	Airtight performance of building enclosure	0.160	0.45	0.33	0.14	0.08
	Internal and external shading	0.290	0.19	0.22	0.19	0.40
Energy efficiency of construction equipment						
0.21	Equipment efficiency of HVAC	0.683	0.54	0.25	0.17	0.04
	Energy efficiency of lighting installation	0.106	0.15	0.49	0.14	0.22
	Equipment efficiency of water supply and drainage system	0.105	0.53	0.21	0.07	0.19
	Efficiency of elevator equipment	0.106	0.63	0.09	0.17	0.11
Construction's operation and management						
0.19	Building energy saving management system	0.369	0.26	0.31	0.22	0.21
	Qualifications of realty management enterprise	0.264	0.33	0.32	0.21	0.14
	the extension of energy saving knowledge	0.210	0.2	0.28	0.29	0.23
	The statistic and publication of energy consumption	0.157	0.15	0.49	0.14	0.22
Comfort and health						
0.21	Indoor thermal and humidity environment	0.425	0.54	0.22	0.06	0.18
	Indoor acoustic and optical environment	0.135	0.58	0.26	0.06	0.10
	Indoor air quality	0.440	0.22	0.24	0.37	0.17

action of all factors but also continue to have all messages in single factor evaluation. Similarly:

$$B_2 = (0.468 \quad 0.210 \quad 0.193 \quad 0.129)$$

$$B_3 = (0.507 \quad 0.254 \quad 0.156 \quad 0.082)$$

$$B_4 = (0.249 \quad 0.335 \quad 0.220 \quad 0.197)$$

$$B_5 = (0.405 \quad 0.234 \quad 0.196 \quad 0.165)$$

The B_1, B_2, B_3, B_4, B_5 form the fuzzy comprehensive evaluation matrix of residential area's building energy efficiency:

$$R = (B_1, B_2 B_3, B_4, B_5)^T = \begin{bmatrix} 0.298 & 0.353 & 0.245 & 0.104 \\ 0.468 & 0.210 & 0.193 & 0.129 \\ 0.507 & 0.254 & 0.156 & 0.082 \\ 0.249 & 0.335 & 0.220 & 0.197 \\ 0.405 & 0.234 & 0.196 & 0.165 \end{bmatrix}$$

From Table 1, we can get A = (0.17, 0.20, 0.21, 0.19, 0.21), so the fuzzy evaluation result of total factor is:

$$C = A \circ R = (0.389 \quad 0.275 \quad 0.201 \quad 0.135)$$

Based on the principle of maximum membership degree, the evaluation grade of this area's building energy efficiency can be assessed for "Good".

CONCLUSION

Taking into account the characteristics of the large-scare public building energy saving measures in the hot summer and warm winter area, the evaluation model established to comprehensively evaluate the energy-saving effects of large-scale public building. The contribution of this thesis is as following:

First, the Fuzzy Comprehensive Evaluation Model (FCEM) established basing on the basic principle of fuzzy mathematics, from the perspective of life cycle of buildings.

Second, FCEM can be divided into three levels of the macro, meso and micro and including five stages of architectural design, thermal performance of building enclosure , Energy efficiency of construction equipment, operation management and comfort and health, also including 21 particular targets which makes the evaluation be more targeted.

Third, the fuzzy comprehensive evaluation model was Used to evaluate the energy-saving of large-scare public building in Xiamen city and the evaluation grade of this area's energy-saving can be assessed for "Good" which can provide a reference for the energy-saving evaluation of public building.

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