

Multi-Hierarchical Gray Correlation Analysis Applied in the Selection of Green Building Design Scheme

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Abstract. As a sustainable form of ecological structure, green building is widespread concerned and advocated in society increasingly nowadays. In the survey and design phase of preliminary project construction, carrying out the evaluation and selection of green building design scheme, which is in accordance with the scientific and reasonable evaluation index system, can improve the ecological benefits of green building projects largely and effectively. Based on the new Green Building Evaluation Standard which came into effect on January 1, 2015, the evaluation index system of green building design scheme is constructed taking into account the evaluation contents related to the green building design scheme. We organized experts who are experienced in construction scheme optimization to mark and determine the weight of each evaluation index through the AHP method. The correlation degree was calculated between each evaluation scheme and ideal scheme by using multilevel gray relational analysis model and then the optimal scheme was determined. The feasibility and practicability of the evaluation method are verified by introducing examples.

1. Introduction

At present, the environmental problems in Chinese economic and social development are becoming more and more prominent. There are many factors which may cause these issues. However, it is the undoubtedly important reason that being too concerned with economic development instead of ecological construction for a long time in the past. Lacking in the eyesight of long-term and sustainable development is the key point as well. Environmental problems have seriously affected people's normal production and life, which means improving and solving environmental problems has become more and more urgent. It is an effective way to solve the current environmental problems by completely changing the traditional industrial production mode with high energy consumption and high pollution. Meanwhile, seeking the transformation and upgrading of the development mode works. Building industry is one of the most resource consumption industries, and the development of green building is an inevitable choice for the transformation and upgrading of China's construction industry^[1].

The General Office of the State Council has clearly put forward that the government should enhance the use efficiency of building materials to a higher degree and vigorously promote the construction industry to carry out energy-saving emission reduction action. Green building should be carried out and developed, and the traditional development mode of the construction industry and the



construction mode of urban and rural should be changed^[2]. This declaration has been put as early as the beginning of 2013 in its forward “green building action program”. Furthermore, *vigorously promoting the construction of ecological civilization* has been written into the 18th Report of the Party as a new concept of ecological development, which is elevated to a new height. The new version of *Green Building Evaluation Criteria*(GB/T50378-2014) began to be implemented nationwide on January 1, 2015 with the development of green building risen to national strategy, and green building in China enters the fast lane of development.

With the continuous acceleration of urban and rural integration process currently, there will be more and more building energy consumption. As a sustainable form of ecological architecture, green building has been attracting widespread concern and advocacy in the whole society. In recent years, the relevant research about green building has gradually become a hot spot, but through research we found that the most investigations are just focused on green evaluation and certification aspects of the existing building, and the effect that initiative to reduce energy consumption and improve the ecological environment is actually relatively limited. In order to reduce effectively building energy consumption and improve the ecological benefits of the building greatly, it may be considered that we select the better *green* design scheme by evaluation of project design according to certain evaluation criteria during the survey and design stage of the project. This measure can not only enhance the overall ecological benefits of green building projects, but also guide the constructor and investors on their own initiative to focus on green building and protect the ecological environment^[3].

2. Construction of Evaluation Index System

The primary step of the comprehensive evaluation is to select a series of suitable evaluation indexes, which are the basis for comprehensive evaluation and optimization of the evaluation schemes. Whether the selection of index is suitable or not has a great influence on the result of comprehensive evaluation. Green building design is a complex system engineering. Evaluation on advantages and disadvantages of a design scheme, involving many aspects of many factors, needs to use scientific methods to consider the overall line. China's earlier “*Green Building Evaluation Standards*” was proposed in 2006 based on a large number of other countries' advanced experience, which has been used until the end of 2014. The new version of the evaluation criteria came into force on January 1, 2015 officially and the original standard was abolished at the same time. Compared with old one, the new version made a certain adjustment in the selection of indicators more comprehensive and refined. When constructing the evaluation index system of green building design, we based on the new evaluation criteria. Meanwhile, we focused on the evaluation content related to the green building design scheme, from 6 aspects to build the index system, the specific selection of the 14 evaluation indicators, which are shown in Table 1 as follows.

Table 1. Comprehensive Evaluation Index System of Green Building Design Scheme

Comprehensive Evaluation of Green Building Design Scheme (A)	Energy Saving (B ₁)	Energy conservation (C ₁)
		Development and utilization of new energy (C ₂)
	Water Saving (B ₂)	Water-saving capacity (C ₃)
		Development and utilization of unconventional water resources (C ₄)
	Material Saving (B ₃)	Saving material (C ₅)
		The safety of the material (C ₆)
		Recycling of materials (C ₇)
	Land Saving (B ₄)	Effective use of land (C ₈)
	Indoor Environment (B ₅)	Impact on the surrounding environment (C ₉)
		Air quality (C ₁₀)
	Construction and Operation Management (B ₆)	Acousto-optic-thermal environment (C ₁₁)
		Construction management (C ₁₂)
		Garbage disposal (C ₁₃)
		Intelligent equipment (C ₁₄)

3. Determine the Weight of the Evaluation Index

The weight of the evaluation indexes reflects the importance of an index relative to the previous level. Taking into account that the evaluation index system of the green building design schemes involves many factors, specifically containing 6 major indicators and 14 specific indicators, which interact each other, it is more appropriate that the AHP method is selected to determine the weight.

3.1. Analytic Hierarchy Process

Analytic Hierarchy Process, AHP for short, is a commonly used multi criteria decision-making method, which is characterized by a good implementation of qualitative and quantitative analysis of the organic combination. This method was come up by T.L.Satty et al, who was a well-known management and operation scientist in the United States in the 70s of the last century. This method is based on the quantitative analysis of human subjective judgment, and carries on the quantitative analysis on this basis, which has the characteristics of gradual stratification^[4]. The AHP method is often used to solve some complex multi-criteria decision problems as a decision tool, which is highly applicable. Its specific mathematical model is described as follows.

3.1.1. Construction of Judgment Matrix. A represents target set, and a_i, a_j are both factors of evaluation ($i=1, 2, \dots, m; j=1, 2, \dots, n$). The relative importance of any two indicators of the same level in the matrix are compared with each other, with a_{ij} expresses the importance coefficient of a_j relative to a_i , the ratio ω_i/ω_j of the relative weight of the two factors can be obtained. To sort the evaluation factors according to their important degree, we can build the evaluation index judgment matrix A as follows:

$$A = \begin{bmatrix} 1 & \frac{\omega_1}{\omega_2} & \dots & \frac{\omega_1}{\omega_n} \\ \frac{\omega_2}{\omega_1} & 1 & \dots & \frac{\omega_2}{\omega_n} \\ \frac{\omega_1}{\omega_3} & \frac{\omega_2}{\omega_3} & \dots & \frac{\omega_1}{\omega_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\omega_n}{\omega_1} & \frac{\omega_n}{\omega_2} & \dots & 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix}$$

In the above judgment matrix, the 1-9 scale method is used to quantify and express the importance of an element relative to another one. As shown in Table 2 is the specific digital scale value when two elements compared, which explained the intensity with the different values of 1-9 when low-level elements compared to high-level (criterion layer) elements in the multilevel structure^[5].

Table 2. 1-9 Scale Method

Relative Importance (C_{ij} assignment)	Definition	Importance Expression
1	Equal importance	Two elements with i and j act the same
3	Slightly	The i element is more important than element j slightly
5	Strong	The i element is obviously important than j element
7	Very strong	The i element is more important than element j strongly
9	Absolutely important	The i element is extremely important than element j
2, 4, 6, 8		Other relative values of scale
Reciprocal value		$C_{ij}=1/C_{ji} (i \neq j)$

3.1.2. Calculate the weight vector and the maximum characteristic root λ_{max}

1) The product of each row in the judgment matrix is calculated by M_i

$$M_i = \prod_{j=1}^n a_{ij}, \quad i = 1, 2, \dots, m$$

2) To M_i open m root mean square, and then get \overline{W}_i

$$\overline{W}_i = \sqrt[m]{M_i} = [\overline{W}_1, \overline{W}_2, \dots, \overline{W}_m]^T$$

3) The vector i is normalized to get the feature vector W_i

$$W_i = \frac{\overline{W}_i}{\sum_{i=1}^m \overline{W}_i}, \quad i = 1, 2, \dots, m$$

Then the weight vector $W = [w_1, w_2, \dots, w_n]^T$.

4) Calculating the maximum characteristic root of the judgment matrix $A = (a_{ij})_{m \times n}$

$$\lambda_{\max} = \frac{1}{m} \sum_{i=1}^m \frac{(AW)_i}{W_i}$$

3.1.3. Consistency check. The judgment matrix should be checked for consistency: $CR = CI/RI < 0.1$. It is considered acceptable only when $CR < 0.1$, otherwise the judgment matrix must be readjusted^[6]. Where, CI expresses consistency index, $CI = \frac{1}{m-1}(\lambda_{\max} - m)$. RI expresses average random consistency index, for the 1~9 order judgment matrix, the value of RI is shown in Table 3.

Table 3. The Average Random Consistency Scale Values for RI

m	8	9	10	11	12	13	14
RI	1.28	1.32	1.37	1.41	1.43	1.45	1.46

3.2. Determination of Index Weight

Organization experts scoring and taking into account all aspects of factors to determine the structure of the matrix, according to the previous steps, through the consistency test, we can determine the various levels of indicators weight values of the green building design schemes as follows:

$$W_{AB} = (0.16, 0.24, 0.12, 0.08, 0.22, 0.18)$$

$$W_{B1C} = (0.62, 0.38)$$

$$W_{B2C} = (0.75, 0.25)$$

$$W_{B3C} = (0.36, 0.40, 0.24)$$

$$W_{B4C} = (0.72, 0.28)$$

$$W_{B5C} = (0.52, 0.48)$$

$$W_{B6C} = (0.32, 0.34, 0.34)$$

4. The Basic Model of Multilevel Gray Relational Analysis

The system of green building design is a gray system with incomplete information, where the multilevel gray correlation analysis method is adopted to carry out evaluation research, specifically using the method to analysis quantitatively the correlation degree between the two factors in the system. The basic idea is, the optimal index value of the evaluation scheme is used as each entity element x_{0k} of the reference series X_0 , and that each index of the evaluation scheme is taken as the entity element x_{ik} of the comparison series X_i , and then the gray relational degree r_i between the reference series and the comparison series can be calculated^[7]. According to the value of r_i we can judge the closeness degree of each decision scheme and ideal scheme, and then the order of pros and cons with each evaluated scheme can be determined.

4.1. Constructing Reference Series

The evaluation value of the No. k index of the No. i evaluated scheme is expressed by v_{ik} ($i=1,2,\dots,m$; $k=1,2,\dots,n$), V_0 represents the reference series, which is usually made up of the best value v_{0k} in the m evaluated schemes, $v_{0k}=\text{Optimum}(v_{ik})$, and then $V_0=(v_{01},v_{02},\dots,v_{0n})$.

For a specific gray system (supposing the system has m evaluation objects and n evaluation indicators), the matrix exists as follows:

$$V=(V_{ik})_{m \times n} = \begin{bmatrix} V_{11} & V_{12} & \cdots & V_{1n} \\ V_{21} & V_{22} & \cdots & V_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ V_{m1} & V_{m2} & \cdots & V_{mn} \end{bmatrix}$$

And then $V_0=(V_{01},V_{02},\dots,V_{0n})$, so the reference sequence V_0 will can be constructed.

4.2. Standardized Processing of Index Values

In order to facilitate the comparison of each evaluation index, the index values are to be standardized according to the formula(1).

$$X_{ik} = \frac{V_{ik} - \min_i V_{ik}}{\max_i V_{ik} - \min_i V_{ik}} \quad (1)$$

After standardized treatment:

$$X=(X_{ik})_{m \times n} = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & \cdots & X_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ X_{m1} & X_{m2} & \cdots & X_{mn} \end{bmatrix} \quad (2)$$

4.3. Calculating Correlation Coefficient

The sequence $X_i=(X_{i1}, X_{i2}, \dots, X_{in})(i=1,2,\dots,m)$ is as a comparison sequence, and $X_0=(X_{01}, X_{02}, \dots, X_{0n})$ as the reference sequence, ζ_{ik} represents the correlation coefficient, it can be calculated according to the formula (3) as follows.

$$\zeta_{ik} = \frac{\min_i \min_k |X_{0k} - X_{ik}| + \rho \max_i \max_k |X_{0k} - X_{ik}|}{|X_{0k} - X_{ik}| + \rho \max_i \max_k |X_{0k} - X_{ik}|} \quad (3)$$

In the above formula(3): ζ_{ik} expresses correlation coefficient of the first k evaluation index with the comparison sequence X_i and the reference sequence X_0 , ρ is resolution coefficient, $\rho \in [0,1]$, generally $\rho=0.5$. So correlation coefficient matrix is as follows.

$$E=(\zeta_{ik})_{m \times n} = \begin{bmatrix} \zeta_{11} & \zeta_{12} & \cdots & \zeta_{1n} \\ \zeta_{21} & \zeta_{22} & \cdots & \zeta_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \zeta_{m1} & \zeta_{m2} & \cdots & \zeta_{mn} \end{bmatrix} \quad (4)$$

4.4. Calculating the Correlation Degree of Single Hierarchy

W represents the weight vector of a certain index layer relative to the previous one, $W=(w_1, w_2, \dots, w_n)$

($\sum_{k=1}^t w_k = 1$, t is the total number of the index), and so the correlation degree R is as follows:

$$R=(r_i)_{1 \times m} = (r_1, r_2, \dots, r_m) = WE^T \quad (5)$$

4.5. Calculating the Final Correlation Degree

Supposing that there is a multilevel system which has a total of L layers, the final gray correlation is calculated as follows: The correlation coefficient of the k -th layer index is calculated synthetically and it is obtained that the correlation degree of each index of the layer ($k-1$) of the system. And then, on the basis of the correlation degree of the layer, the previous layer ($k-2$) is continued to be synthesized, and so on, and finally the correlation degree of the highest level of the system will be found out, which is the ultimate correlation degree of the multilevel system^[8]. According to the size of the system's final correlation degree $r_i (i=1,2,\dots,m)$, you can determine the order of the pros and cons of each program, so as to achieve the purpose of schemes optimization.

5. An Example

A green building project is in the stage of design and investigation, design units need refer to the *Green Building Evaluation Criteria* (GB/T50378-2014) to complete the program design. Now there are 5 alternative options for the final design, and 5 experts who are familiar with the field will be invited to optimize the options.

5.1. Constructing Evaluation Index System

The evaluation index system of green building design scheme is constructed as shown in Table 1. Among them, the first layer for the target layer is the green building design (A). The second layer is the standard layer, which is a total of 6 layers, and including energy conservation (B_1), water saving (B_2), materials saving (B_3), land saving (B_4), indoor environment (B_5) and construction and operation management (B_6). The third layer includes 14 indicators with C_1, C_2, \dots, C_{14} , which is the index layer.

5.2. Calculating the Correlation Degree of Single Layer

According to the *Green Building Evaluation Criteria* and the evaluation contents related to the design schemes, the experts used the 10-point system to score the five design schemes (V_1, V_2, V_3, V_4, V_5) respectively, we can get the value of each index $V_{ik} (i=1,2,3,4,5; k=1,2,\dots,14)$ as shown in Table 4, and the optimum value V_{0k} of each index.

Table 4. Evaluation Index Value and Optimal Value of Green Building Design

Index	Scheme					Optimum Value
	V_1	V_2	V_3	V_4	V_5	
C_1	7	7	8	6	8	8
C_2	8	8	7	6	6	8
C_3	7	7	7	7	8	8
C_4	8	7	7	6	8	8
C_5	7	8	6	6	6	8
C_6	4	8	8	7	8	8
C_7	5	7	5	5	8	8
C_8	9	6	7	5	7	9
C_9	6	5	6	5	7	5
C_{10}	6	5	5	7	5	7
C_{11}	8	6	8	7	6	8
C_{12}	8	7	6	5	7	8
C_{13}	7	8	5	6	7	8
C_{14}	5	6	7	6	6	7

From Table 4, we can get the reference sequence $V_0=(8,8,8,8,8,8,9,5,7,8,8,8,7)$.

After the normalization of each index in Table 4 according to formula(1), we can calculate the correlation coefficient ζ_{ik} according to formula(3) as shown in Table 5.

Table 5. Correlation Coefficient Values

Correlation Coefficient	Scheme				
	V ₁	V ₂	V ₃	V ₄	V ₅
ζ_{i1}	0.5	0.5	1	1/3	1
ζ_{j2}	1	1	0.5	1/3	1/3
ζ_{i3}	1/3	1/3	1/3	1/3	1
ζ_{i4}	1	0.5	0.5	1/3	1
ζ_{i5}	0.5	1	1/3	1/3	1/3
ζ_{i6}	1/3	1	1	2/3	1
ζ_{i7}	1/3	0.6	1/3	1/3	1
ζ_{i8}	1	0.4	0.5	1/3	0.5
ζ_{j9}	0.5	1	0.5	1	1/3
ζ_{i10}	0.5	1/3	1/3	1	1/3
ζ_{i11}	1	1/3	1	0.5	1/3
ζ_{i12}	1	0.6	3/7	1/3	0.6
ζ_{i13}	0.6	1	1/3	3/7	0.6
ζ_{i14}	1/3	0.5	1	0.5	0.5

5.3. Multilevel Structure Correlation Degree Synthesis

The weight of the indexes has been identified in the previous section 3.2, the correlation degree of the indexes of layer B can be calculated according to formula (5).

$$R_{B_1} = W_{B_1C} \cdot E_{B_1C}^T = (0.62, 0.38) \cdot \begin{bmatrix} 0.5 & 0.5 & 1 & 1/3 & 1 \\ 0.5 & 1 & 0.5 & 1/3 & 1/3 \end{bmatrix}$$

$$= (0.69, 0.69, 0.81, 0.333, 0.747)$$

Similarly we can obtain as follows.

$$R_{B_2} = W_{B_2C} \cdot E_{B_2C}^T = (0.500, 0.375, 0.375, 0.333, 1.000)$$

$$R_{B_3} = W_{B_3C} \cdot E_{B_3C}^T = (0.393, 0.904, 0.600, 0.467, 0.760)$$

$$R_{B_4} = W_{B_4C} \cdot E_{B_4C}^T = (0.860, 0.568, 0.500, 0.520, 0.453)$$

$$R_{B_5} = W_{B_5C} \cdot E_{B_5C}^T = (0.740, 0.333, 0.653, 0.760, 0.333)$$

$$R_{B_6} = W_{B_6C} \cdot E_{B_6C}^T = (0.637, 0.702, 0.590, 0.422, 0.566)$$

Similarly, the correlation degree of the indicators of the highest layer A can be obtained:

$$R_A = (r_1, r_2, r_3, r_4, r_5) = W_{AB} [R_{B_1}, R_{B_2}, R_{B_3}, R_{B_4}, R_{B_5}, R_{B_6}]$$

$$= (0.160, 0.240, 0.120, 0.080, 0.220, 0.180) \cdot \begin{bmatrix} 0.690 & 0.690 & 0.810 & 0.333 & 0.747 \\ 0.500 & 0.375 & 0.375 & 0.333 & 1.000 \\ 0.393 & 0.904 & 0.600 & 0.467 & 0.760 \\ 0.860 & 0.568 & 0.500 & 0.520 & 0.453 \\ 0.740 & 0.333 & 0.653 & 0.760 & 0.333 \\ 0.637 & 0.702 & 0.590 & 0.422 & 0.566 \end{bmatrix}$$

$$= (0.624, 0.554, 0.582, 0.474, 0.662)$$

5.4. Scheme Optimization

According to the calculation results of RA, we can get the order of the five alternative design schemes:

$$V_5 > V_1 > V_3 > V_2 > V_4.$$

6. Conclusion

Based on the new *Green Building Evaluation Criteria*, taking into account other factors that may have an impact on the selection of green building design, we construct the evaluation index system of green

building design scheme. The gray comprehensive evaluation method is used to evaluate the green building design scheme, and the optimal green building design scheme is determined with examples. The scientific and practicability of the gray relational analysis method is verified.

With the above analysis, we can draw the following conclusions:

(1) Gray system is a kind of uncertain system with partial information known and partial information unknown. The evaluation system of green building design has the typical “gray” characteristics, because that the evaluation factors are very many and complex, there are difficulties in the selection of the factors, and some data of the indexes selected are known, but the others unknown. Therefore, it is appropriate to use gray system theory for analysis and evaluation.

(2) The gray relational analysis method is used to evaluate the green building design scheme, which can commendably achieve the organic combination of qualitative judgment and quantitative analysis, and improve the scientificity of decision-making, and it has strong practical significance. But it should be pointed out that using this method is only for horizontally comparing the pros and cons of each evaluation scheme and then choose the best scheme, but it can not truly reflect the absolute level of the pros and cons of each evaluation scheme.

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