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Evaluation of green and sustainable building project based on extension matter-element theory in smart city application

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Abstract

The postoccupancy performance and operation management level of green building largely determines the overall sustainability level of green buildings. It is necessary to evaluate the degree of success of green buildings in the operation stage to ensure the implementation effect of the whole life cycle. However, the current green building evaluation system is incomplete, and the research on the degree of success evaluation of green buildings is very lacking. It is necessary to establish a scientific and effective evaluation index system to evaluate the degree of success of green buildings. This article applies the extension matter-element theory and entropy method to evaluate the degree of success of green building projects, taking a green building project in Nanchang as an example, and seven experts were invited to score and evaluate the project's degree of success by calculating the relevance degree of each evaluation index. The results show that this green building's degree of success emerged as at level II, that is, the "generally successful" level, and each first-level indicator, respectively, lay at level III, level II, level II, and level II. The case study proves that the evaluation method of green building determined in this article is scientific and reliable.

KEYWORDS

correlation function, entropy method, extension matter-element theory, green building, project evaluation

1 INTRODUCTION

The construction industry is notable for its characteristics of high energy consumption and high pollution. Traditional buildings can no longer meet the requirements of green economic development,[1] making it imperative to develop green buildings. In recent years, China's green buildings have developed rapidly. As of the end of September 2016, there were 4515 "green building" labeled projects nationwide, with a total floor area of 52.317 million square meters. However, there were only 269 operating labels, with a floor area of 36.76 million square meters, accounting for 6% and 7% of the total area, respectively.[2] The greatest hindrance lies with the quantitative imbalance between the green building design and operation phases, while more than 80% of energy consumption occurs during the actual occupancy operation stage rather than during the construction stage, which indicates that the postoccupancy performance of green building largely determines the overall sustainability level.[3] It is necessary to provide good management services in later operational stage for green buildings because the initial stage cost is certain, so as to make these buildings a more popular residential choice and valued space of development, and to ensure that "green" management is the key link for realizing green building's value function in the operation stage. In order to ensure the implementation effect of a green building's life cycle, it is necessary scientifically and correctly to evaluate the design and operation of this effect. Evaluating the degree of success of a green building is a powerful means to maintain the "green" operation of such buildings. Evaluations of this type mainly embody the feedback and feedforward pertaining to a green building operation and promote the improvement of green buildings, making their operation more scientific and efficient.[4]

Evaluation standard for green building (ESGB) is one of the main technical bases for carrying out and evaluating the green building practice. Currently, there are some representative green building assessment schemes of countries worldwide, for example, BREEAM developed by Britain, LEED developed by the USA, GB Tool (Canada). In 2006, the MOHURD issued a voluntary building environmental assessment scheme, named ESGB (abbreviated as ESGB 2006),[5] and revised this standard in 2014 (abbreviated as ESGB 2014),[6] with the purpose of addressing the conservation of energy, water, material, and site and protection of outdoor and indoor environment. Among the building environmental assessment schemes brought in China, BREEAM and LEED are the two most representative building environmental schemes.[7] The existing evaluation standards already include the contents of operation and management, but the research focus is still on energy saving, water saving, material saving, site selection, and indoor and outdoor environmental quality. The proportion of operation management in the evaluation system is also very low. For example, in China's new ESGB, the weight of operation management is only 10%, and there are too many qualitative indicators and lack of quantitative indicators.[8] Moreover, although China's evaluation standard system for green building stipulates the weight of each first-level evaluation indicators, the subitems included in the first-level indicators are only listed in a side-by-side relationship, and the importance is not indicated, and the provisions of the evaluation system are not clear enough.[9]

Scholars' research on green building evaluation is also concentrated in the construction and design stages. There is a significant lag in obtaining certification during the operational stages of green buildings.[10] Sharif et al[11] developed an implementation framework for green buildings in Malaysia but focused on the initial implementation of the green building, and the operational stage is not included in the research. Huang and Wang[12] put forward the evaluation index system of construction engineering's green construction level and focuses on the establishment of index weights. Other research studies on the evaluation of green buildings focus on the cost-effectiveness[13] and environmental quality[14,15] of green buildings. Uğur and Leblebici[16] also evaluated the cost-benefit analysis and payback period of two green buildings located in Turkey according to the LEED certification system, and the evaluation on the degree of success of green building projects in the operation stage is still very lacking.

The degree of success evaluation is a method to evaluate the overall success of a project according to the implementation and operation of the project and with a certain project index as the standard or target. This method usually evaluates the degree of success of the project by the experience of the evaluation experts or expert groups. Before evaluating the degree of success, it is necessary to design and establish a scientific and reasonable project evaluation index system in advance.[17] The advantages of the degree of success evaluation method are clear conclusion, simple method, and strong operability. It is easy for decision-makers to obtain and understand the overall evaluation conclusion of the project. And the method is efficient, time-saving, high accuracy, and can complete the evaluation of multilevel indicators; from the perspective of expert participation, the expert participation of this method is strong, but the number of experts is not much required.[18]

However, China's current system of evaluating green buildings emphasizes the early stage over the late stage, and investment over consumption; it also emphasizes the evaluation of design and development but ignores the postoperation evaluation,[19] thus directly affecting the scientific rigor of evaluation of green building projects.

At present, the methods of success evaluation mainly include Grey theory,[20] Delphi method,[21] Fuzzy neural network,[22] Fuzzy evaluation method,[23] logical framework approach,[24] BP neural network,[25] and so on. However, each of these methods has its own disadvantages. For example, the insufficiency of fuzzy comprehensive evaluation is that the calculation of multiobjective and multilevel evaluation models is very complicated. The correlation degree calculated by the grey comprehensive evaluation method cannot fully consider the connection between evaluation objects. The Delphi method has great subjective one-sidedness. From this, a new approach to evaluating the degree of success of green building projects can be obtained.

Matter-element extension model, established and developed by Chinese scholars Cai et al in 1983, can analyze qualitatively and quantitatively the contradiction problem based on the formalized logic tools.[26] The matter-element model is composed of objects, characteristics, and values based on certain characteristics. Therefore, the content and the relationship between the quality and the quantity of the comprehensive evaluation can be clearly illustrated. At the same time, this model has the convenient advantage that it quantifies the qualitative indices.[27] The extension matter-element theory can solve the multifactor evaluation problem well. The evaluation index system of green building success degree includes one general target, several first-level indicators, and more subdivided second-level indicators. It can be seen that the index system is a typical multifactor, multilevel, and multiobjective complex structure. In order to analyze this structure, it is necessary to use the extension matter-element theory which has strong logic and can establish mathematical model methodology, it is necessary to use the method of extension matter-element theory, which has strong logic and can establish mathematical models, to analyze this structure. Extension matter-element theory is widely used in many fields such as green project management evaluation, supplier risk evaluation, project risk management of general contracting, risk research of local government investment and financing platforms, and project safety evaluation. On the basis of the existing research, it is a desirable practice to introduce the extension matter-element theory into the degree of success evaluation research of green building that has not yet been involved.

In this article, based on qualitative and quantitative analysis, this extension matter-element model is applied to evaluate the degree of success of green building projects. This article comprises the following: Section 2 establishes an evaluation model for the degree of success of green building projects. Section 3 establishes an evaluation model for the degree of success of green building projects based on the extension matter-element method and entropy weight method. Section 4 takes a specific green building project as an example and evaluates the risks involved the success degree. Section 5 concludes this article. The last section is the limitations of this research and future work.

2 | CONSTRUCTION OF INDEX SYSTEM

In 2014, China issued the "ESGB" (GB/T 50378-2014), and revised the "ESGB" (GB/T 50378-2006) issued in 2006,including seven aspects: land saving and outdoor environment, energy saving and energy utilization, water saving and water resource utilization, material saving and material resource utilization, indoor environment quality, construction management, and operation management, which are divided into two stages: design evaluation and operation evaluation. The operation evaluation shall be carried out one year after the building passes the completion acceptance and is put into use. The main focus of this study is on the evaluation of the green building operation stage, and the operation management is the key evaluation content. Construction management has been completed during design evaluation after completion acceptance, so construction management is eliminated. The operation management is listed as a primary evaluation indicator separately, and the other five contents are used as the second-level evaluation indicators under the first-level evaluation index of the building function evaluation.

In the existing research, in addition to only according to the "ESGB" to build the evaluation system,[28,29] the evaluation system of green building mainly includes operation efficiency, transformation efficiency, and financial efficiency[30]; user satisfaction, running time, operating efficiency, cost-effectiveness ratio[31]; and objective evaluation, financial evaluation, social impact evaluation, and environmental impact evaluation.[32] It mainly includes financial evaluation, operation evaluation, social impact evaluation, environmental impact evaluation, user satisfaction, and so on.

The "ESGB" formulated by China mainly controls whether the required technology or measures adopted by green buildings are in place. Existing research on green building evaluations focuses on the impact of these buildings on the environment, the use of resources, and the control of costs. The lack of integrity and life periodicity in the evaluation of green buildings has arguably enabled developers' short-term interest behaviors, and the transferring of costs to the operation period of green buildings or to consumers, leading to the low operation efficiency of green buildings. The latter has, in turn, adversely affected the quality of the external environment, thus reducing consumers' willingness to choose green buildings and restricting their development.[33] The operation and use of green buildings are, ultimately, reflected in the cost-benefit analysis of consumers and users, with a financial evaluation also forming an important part of the evaluation of green buildings.[34] Based on the existing research, financial evaluation indicators should also be included in the degree of success evaluation system of green building projects.

While evaluating the green building itself, it is also necessary to pay attention to the external evaluation, such as user satisfaction. In 1999, Drury Crawley proposed that green buildings should be evaluated based on market demand while considering their life cycle.[35] The ultimate purpose of the building is to better serve the users of the building and create a safe, healthy, and comfortable use environment for them. Therefore, in the operation system that accounts for a large proportion of the life cycle of the green building, we should increase the proportion of the evaluation of the users' needs, that is, to evaluate the building from the perspective of the users. At the same time, green buildings also have significant externalities. Considering the impact of technology, economy, environment, and society comprehensively, the user satisfaction and external influence of buildings are taken as the dimensions of social impact evaluation, together with financial evaluation, building function evaluation, and operation management evaluation, constitutes the evaluation system of this article.

To sum up, this article draws on the ESGB and Green Building Post-Assessment Technical Guide issued by the Ministry of Housing and Construction and refers to relevant literature.[4,31,33,36-39] Experts in related fields were also consulted in order to determine the evaluation index system of green buildings' success, based on the established evaluation index system. In line with the postproject evaluation ideas and the premise of meeting the principles of scientific standardization, operability, rationality, and consistency, the established index system took financial evaluation, social impact evaluation, building function evaluation, and operation management evaluation as the main evaluation indicators. There are four first-level indicators and 13 second-level indicators, as shown in Table 1.

1. *Financial evaluation*: It is essential to analyze the financial perspective of any project. For green buildings, developers need to analyze the cost benefit of their projects at the operational stage, which is especially important for the purpose of cost savings and expense reductions throughout the construction of ordinary buildings. This is an important factor in encouraging developers to build green buildings.
2. *Social impact evaluation*: The impact of green buildings includes both the internal and external aspects of the building. The internal refers to the impact on the building's users, reflected

TABLE 1 Evaluation index system of the success of green buildings

Evaluation index system	First-level indicators	Second-level indicators
Success-degree evaluation of green building α	Financial evaluation β_1	Payback period δ_{11}
		Cost saving rate δ_{12}
		Rate of return on investment δ_{13}
	Social impact evaluation β_2	User satisfaction δ_{21}
		External influence δ_{22}
		Green compliance δ_{31}
		Land utilization δ_{32}
	Building function evaluation β_3	Energy conservation and emission reduction δ_{33}
		Material saving and water saving capacity δ_{34}
		Indoor environmental quality δ_{35}
	Operation management evaluation β_4	Management regulation δ_{41}
		Technical management δ_{42}
		Environmental management δ_{43}

in the latter's satisfaction. Green buildings also exert an external influence owing to the significant positive externalities in the production and consumption of green buildings; moreover, the development of green buildings has a diffusion effect, thus further making it necessary to evaluate their external impact.

3. *Building function evaluation*: The evaluation of building function mainly focuses on the application, effect, and function of green technology. This article judges the degree of success of the function dimension with reference to the effect of green buildings in environmental protection, energy conservation, and emissions reduction and establishes a secondary indicator system that includes green compliance, land utilization, energy conservation and emission reduction, material saving and water saving capacity, and indoor environmental quality.
4. *Operation management evaluation*: Operation management forms the basis for the later operation of green building projects and is the embodiment of the green building concept. This aspect relies on management regulation, management awareness, and administrators' appropriate competence. According to the ESGB (GB/T50378-2014) and Green Building Post-Assessment Technical Guide, the operation management evaluation is embodied in three aspects, including management regulations, technical management, and environmental management.

3 | MODEL CONSTRUCTION

3.1 | Extension matter-element theory

The extension matter-element method is an evaluation method put forward by a Chinese scholar, Cai Wen. It takes matter-element as a logical cell, establishes an extension model to solve contradiction problems, studies the basic properties of matter-element, and sets lays the theoretical foundation and reasoning framework for solving contradiction problems.[40] New methods of extension matter-element analysis were created and adapted to suit its applications in system theory. Systems were considered as a set of matter-elements, with each element consisting of objects, characteristics, and values, which participate in a range of processes and transformations.[41,42] Compared with classical mathematics, extension theory focuses more on the problem itself than data or form, and its application range is more extensive. It uses matter-element and its correlation to provide a formal model of the research problem; extension matter-element set and correlation function quantitatively to analyze the incompatibility problem, and, finally, converts an incompatibility problem into a compatibility problem through matter-element transformation.[43]

Following on from this idea, matter-element analysis now includes the following basic steps: first, the system is divided into matter-elements (objects). Analysis or evaluation factors are then selected and classes are defined. Class intervals for each factor are then also defined. For each class, the range of values is called the classical domain, while the whole range of values for all classes is called the segmented domain. Third, the correlation degree for each single factor (in other words, how well each factor matches the criteria for the category) is calculated. Finally, the integrated correlation degree of matter-elements for each class is calculated through model integration methods such as the weighted average method. The class (which includes the maximum integrated correlation degree) defines the grade the matter-element falls within.

The theoretical pillars are the matter-element method and the extension set theory, and the logical cell is the matter-element theory. Based on the formalize logic tools, the rules and methods required to solve the contradiction problem can be analyzed qualitatively and quantitatively.

TABLE 2 Method comparison

Common method	Disadvantage
Delphi method	Requires a lot of time and workload, and the evaluation results are highly dependent on expert experience.
With and without comparison method	Difficult to accurately predict the outcome of a project that has not occurred.
Before and after comparison	Easy to ignore the influence of external factors.
Principal component analysis	With fuzziness, weights may appear negative, and evaluation results may have large deviations.
BP neural network	High requirements on the sample size, low accuracy.
Fuzzy comprehensive evaluation	The calculation of multiobjective and multilevel evaluation models is very complicated.
Grey theory	The correlation degree calculated by grey theory cannot fully consider the relationship between evaluation objects.
Fuzzy theory	The membership functions, membership degrees, and weights of indicators of different indicators are difficult to determine accurately.
Logical framework method	An abstract logical thinking way, biased in favor of theoretical research.

Therefore, the content and the relationship between the quality and the quantity of the comprehensive evaluation can be clearly illustrated. At the same time, this model has the convenient advantage that it quantifies the qualitative indices. It can also be used in evaluating the diversified and fuzzy model. Consequently, this model has been widely used in many fields, including pattern recognition, scientific decisions, and comprehensive evaluation. Through the value of the degree of success evaluation index system of green buildings, the grades of the degree of success can be deduced using the matter-element method and the extension matter-element theory. In addition, the correlation function can ensure a precise quantitative result. From this, a new approach to evaluating the degree of success of a green building project can be obtained, and the extension matter-element model has obvious advantages in this respect. As shown in Table 2, most of the existing project evaluation methods have certain defects.

There are several typical incompatibility problems in the process of constructing and operationalizing green buildings, which highlight the contradiction between the limitation of resource consumption and the infinity of social demand and between the destructive use of resources and the integrity of ecological environment protection, among other conflicting aspects.[44] Green buildings' degree of success is influenced by many factors, with the influence degree of these factors on this success also differing. It is, therefore, necessary to find an effective evaluation method to solve these problems.

Due to the complexity of the index system for evaluating the success of a green building, the dimensions and attributes of each individual indicator are inconsistent. If individual indicators are evaluated separately and the evaluation results then integrated into the overall evaluation results, it is obvious that there will be incompatibility between the various evaluation indicators. However, the extension matter-element model can integrate each individual index of different dimensions into a matrix during the initial evaluation, establish an overall evaluation, and then use the membership degree to convert various indexes into dimensionless data and incompatible contradictions into compatible relations. The latter can be seen as suitable for the typical multi-index evaluation problem of evaluating the success of green buildings.[45]

3.2 | Evaluation model based on extension matter-element theory

According to the extension matter-element theory, if the object N has the characteristic C and its value is V, then the ordered ternary group $R = (N, C, V)$, composed of N, C, and V, can be used as the basic element to describe the object, which is termed the "matter-element" for short. The formula symbols and their meanings appearing in the article are listed in Table 3.

In the current study, the evaluation grade of a green building was set to N, each index in the index system to C, and the corresponding evaluation value was V. If the object N has m characteristics $C_1, C_2, \ldots, C_m$ and the corresponding values are $V_1, V_2, \ldots, V_m$, the subsequent matter-element matrix composed of these three can be expressed as follows:

$$R = \begin{bmatrix} & C_1 & V_1 \\ N & C_2 & V_2 \\ & \vdots & \vdots \\ & C_m & V_m \end{bmatrix} = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_m \end{bmatrix}, \tag{1}$$

where $R_i = (N, C_i, V_i)$, $(i = 1, 2, \ldots, m)$ is the ith subcharacteristic element matrix of the green building's degree of success, N.

TABLE 3 Explanation of formula symbols

Number	Symbol	Meanings
1	N	Object to be evaluated, that is, the degree of success of green building projects
2	C	Characteristics of the objects being evaluated, that is, the indicators
3	V	Value, which is the score of the indicator
4	R	Matter-element, composed of N, C, and V
5	k	The degree of success of green building is divided into k rating levels
6	N_{nk}	The kth rating level of the degree of success
7	C_{ni}	The characteristics of N_{nk}, representing the ith evaluation indicator constructed
8	V_{nki}	The value range of the evaluation level for the ith index, that is, classical domain
9	a_{nki}	The nth first-level indicator, the lower limit of the value of the classic domain of the kth level
10	b_{nki}	The nth first-level indicator, the upper limit of the value of the classic domain of the kth level
11	N_{np}	All levels of objects to be evaluated
12	C_{ni}	Characteristics of N_{np}
13	V_{npi}	All values of N_{np} for C_{ni}, that is, joint domain
14	$F_k(V_{nm})$	Correlation degree between second-level indicators and each evaluation level
15	$F_k(V_n)$	Correlation degree between first-level indicators and each evaluation level
16	$F_k(V)$	Correlation degree between overall project degree of success and each evaluation level

3.2.1 | Determination of classical domain

The classical domain of matter-element means the range of values the characteristic might take in each level. Thus, if the green building's degree of success has k levels, the value V_{nki} of characteristic C_{ni} would be divided into k intervals, each of which would include the interval $a_{nki}{\sim}b_{nki}$. The green building success rating is divided into k rating levels, and then the matrix of the classical domain could be as follows:

$$R_{nk} = (N_{nk}, C_{ni}, V_{nki}) = \begin{bmatrix} & C_{n1} & V_{nk1} \\ N_{nk} & C_{n2} & V_{nk2} \\ & \vdots & \vdots \\ & C_{nm} & V_{nkm} \end{bmatrix} = \begin{bmatrix} & C_{n1} & (a_{nk1}, b_{nk1}) \\ N_{nk} & C_{n2} & (a_{nk2}, b_{nk2}) \\ & \vdots & \vdots \\ & C_{nm} & (a_{nkm}, b_{nkm}) \end{bmatrix}, \quad (2)$$

where R_{nk} represents the classic domain of level k of the nth first-level indicator.

3.2.2 | Determination of joint domain

The joint domain refers to the range of values of each evaluation index corresponding to the evaluation, that is, the union of the corresponding classic domains, whereby the joint domain of the object to be evaluated is:

$$R_{np} = \begin{bmatrix} & C_{n1} & V_{np1} \\ N_{np} & C_{n2} & V_{np2} \\ & \vdots & \vdots \\ & C_{nm} & V_{npm} \end{bmatrix} = \begin{bmatrix} & C_{n1} & (a_{np1}, b_{np1}) \\ N_{np} & C_{n2} & (a_{np2}, b_{np2}) \\ & \vdots & \vdots \\ & C_{nm} & (a_{npm}, b_{npm}) \end{bmatrix}, \quad (3)$$

where N_{np} is the whole evaluation levels, and the V_{npi} is the value range of C_{ni}.

3.2.3 | Determination of evaluation matter-element matrix

The current study's evaluation material element was determined according to the actual measurement data of each evaluation index based on the green building's degree of success. In the above formula, C_{nm} represents all the second-level evaluation indicators included in the nth first-level indicator; $(\mathrm{a}_{npm}, b_{npm})$ is the joint domain, that is, all the value ranges of the second-level evaluation index C_{nm}.

$$R_{np} = \begin{bmatrix} & C_{n1} & V_{n1} \\ N_{n} & C_{n2} & V_{n2} \\ & \vdots & \vdots \\ & C_{nm} & V_{nm} \end{bmatrix}, \quad (4)$$

where R_n is the matter-element to be evaluated, N_n is the object to be evaluated, and $v_{n1}, v_{n2}, \dots,$ v_{nm} represents the value of N_n with respect to $C_{n1}, C_{n2}, \dots, C_{nm}$.

3.3 | Determination of correlation function

The correlation function indicates the membership degree of each index in the object to be evaluated for each of the set evaluation levels, and $F_k(V_{mn})$ indicates that the mth second-level evaluation index in the nth first-level evaluation index belongs to the kth evaluation level. Thus, the correlation function of the object to be evaluated at each level is as follows[28]:

$$F_k(V_{nm}) = \begin{cases} -\frac{\rho(v_{nm}, V_{nkm})}{V_{nm}}, v_{nm} \in V_{njm} \\ \frac{\rho(v_{nm}, V_{nkm})}{\rho(v_{nm}, V_{npm}) - \rho(v_{nm}, V_{nkm})}, v_{nm} \notin V_{njm} \end{cases},$$

$$\rho(v_{nm}, V_{nkm}) = v_{nm} - \frac{1}{2}(a_{nkm} + b_{nkm}) - \frac{1}{2}(b_{nkm} - a_{nkm}),$$

$$\rho(v_{nm}, V_{npm}) = v_{nm} - \frac{1}{2}(a_{npm} + b_{npm}) - \frac{1}{2}(b_{npm} - a_{npm}), \tag{5}$$

where $\rho(v_{nm}, V_{nkm})$ is the distance from point v_{nm} to interval $[a_{nkm}, b_{nkm}]$, and $\rho(v_{nm}, V_{npm})$ is the distance from point v_{nm} to interval $[a_{npm}, b_{npm}]$.

3.4 | Determining the index weight using the entropy weight method

In the same evaluation system, different weight factors may lead to different or even opposite evaluation conclusions. Therefore, the reasonable determination of weight is of great significance to the evaluation results.[46] For the purposes of this article, the entropy method was used to determine the index weight. As an objective weighting method, the entropy method enables the calculation of the index weight when the weight information is unknown and the interval number of evaluation values is given.[47,48] The entropy value reflects the amount of useful information provided by each evaluation factor for the decision evaluation. The smaller a factor's degree of entropy, the more information the factor provides and the greater its weight. The entropy method can be used to determine the weight of indicators in any evaluation problem and can also eliminate the indicators that contribute less to the evaluation results in the index system, which is more objective than the subjective valuation method.[49] Therefore, in the context of the current analysis, the entropy weight of each index was calculated according to the degree of variation of each index value, and the entropy weight of each index used to weight each index to obtain more objective evaluation results, so as to evaluate the degree of success of green buildings. The advantages of using the entropy method here were 2-fold, namely, objectivity and adaptability. The former indicates a higher level of accuracy and more rigorous objectivity, with the results obtained better explained compared with those obtained via subjective evaluation methods. Adaptability indicates that the entropy method can be used not only in any process where weight needs to be determined, but that it can also be used together with other methods.

The specific calculation processed followed in this study are shown in the following sub-sections.

3.4.1 | Original data matrix

If the number of experts is $N = (N_1, N_2, \ldots, N_m)$, the evaluation index is $C = (C_1, C_2, \ldots, C_m)$ $C = (C_1, C_2, \ldots, C_m)$, and the evaluation value assigned by the expert to the specific indicator can be recorded as X_{ij} $(i = 1, 2,\dots, m; j = 1, 2,\dots, n)$ $X_{ij}(i = 1, 2, \dots, m; j = 1, 2, \dots, n)$, then the raw data matrix can be expressed as follows:

$$X_{ij} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix}. \tag{6}$$

3.4.2 | Dimensionless processing

The original data of all objects should be normalized to eliminate effects of dimension. For the benefit object, the higher its value, the greater its impact, then formula (7) is adopted.

$$Y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})}. \tag{7}$$

For the cost object, the lower its value, the greater its impact, formula (8) is used.

$$Y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})}. \tag{8}$$

Following the dimensionless processing, the standardized matrix X was obtained.

3.4.3 | Entropy calculation of each indicator

If, under the jth indicator, the characteristic weight of the ith evaluation expert is p_{ij}, then $p_{ij} = {}^{Y_{ij}}/\sum_{i=1}^{n} Y_{ij}$ $p_{ij} = {}^{Y_{ij}}/\sum_{i=1}^{n} Y_{ij}$; according to the definition of entropy in information theory, the entropy of the jth indicator can be written as:

$$E_j = -\ln(m)^{-1} \sum_{i=1}^{n} p_{ij} \cdot \ln p_{ij}. \tag{9}$$

3.4.4 | Determining the weight of each indicator

Using the entropy value calculation formula, the entropy value of each index was calculated as E_1, E_2, E_3, …, E_n. The weight of each index calculated according to the entropy value was:

$$W_j = \frac{1 - E_j}{k - \sum E_j} (j = 1, 2, \dots, n). \tag{10}$$

The weight of each factor indicator of the green building evaluation index system could be obtained by applying this model.

3.5 | Correlation degree calculation and level evaluation

The correlation matrix $F_k(V_{nm})$ of the second-level indicators for each evaluation level was calculated using formula (5), and the weights W_j of the second-level indicators, calculated by the entropy method by $F_k(V_{nm})$, were multiplied, so as to calculate the correlation matrix $F_k(V)$ of each first-level index for each evaluation level. That is,

$$F_k(V_n) = W_j \cdot F_k(V_{nm}). \tag{11}$$

The correlation matrix $F_k(V)$ of the object to be evaluated for each evaluation grade was determined by multiplying the weight vector ω of each grade index with the correlation matrix $F_k(V_n)$ of the grade index for each evaluation grade, namely:

$$F_k(V) = \omega \cdot F_k(V_n). \tag{12}$$

If $F_k = \max F_k(V)$, it was determined that the success of the green building lay at the kth level. This article also provides Figure 1 to clearly illustrate the evaluation model.

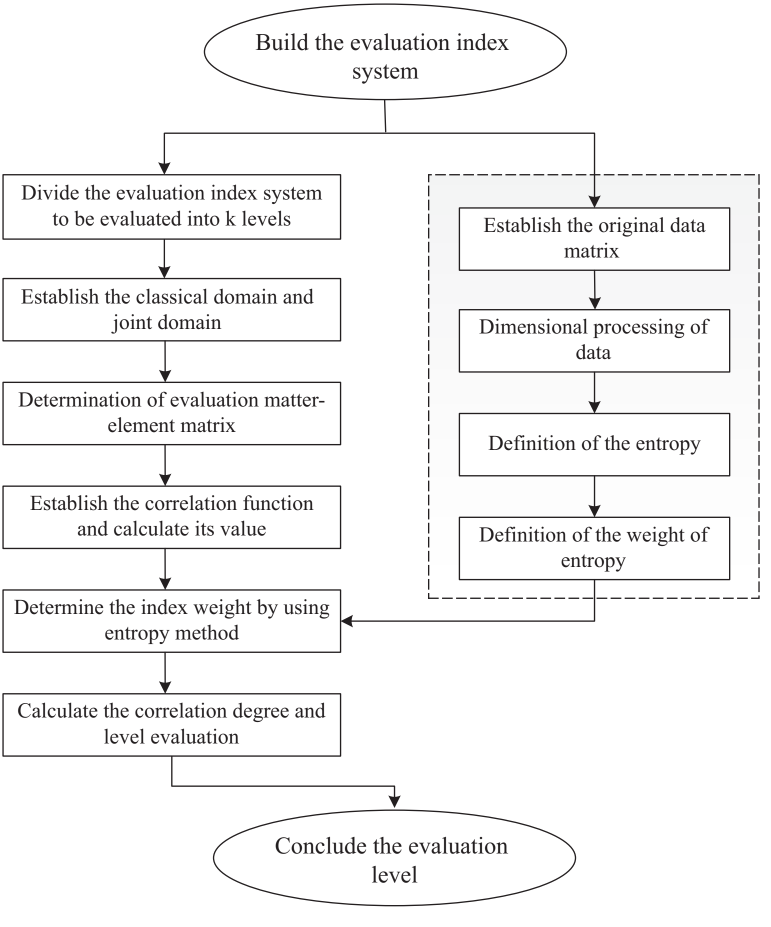

FIGURE 1 Evaluation procedure of the proposed evaluation model

4 | CASE STUDY AND RESULTS ANALYSIS

According to the model built above, and taking a green building with a one-star design evaluation label in Nanchang City of Jiangxi province as an example, the management level of the green building project was quantitatively evaluated; that is, the green building's degree of success was quantitatively evaluated. Based on the evaluation results, specific and targeted improvement suggestions are proposed to improve the life cycle implementation of green buildings.

4.1 | Determination of indicator weights

In this article, seven experts and relevant technical managers in the field of green building were invited to grade the indicators in the green building success evaluation index system according to their own experience, knowledge, evaluation level, and standards, including four professors teaching and researching in construction project management at Jiangxi University of Finance and Economics for more than 10 years and three experts with more than 15 years of project-management experience in the Chinese construction industry. In order to overcome the randomness and irrationality of expert scoring, the consistency of scoring results was checked. The consistency of the expert score data obtained by the α test was 0.783, which is between [0.7, 1)[50] and thus meets the requirements of the consistency test.

The calculated standardized matrix X is:

$$X = \begin{bmatrix} 0.000 & 0.556 & 0.000 & 0.280 & 0.250 & 0.875 & 1.000 & 0.571 & 0.000 & 0.000 & 0.000 & 0.000 & 0.368 \\ 0.111 & 0.667 & 0.286 & 0.040 & 0.875 & 0.500 & 0.563 & 1.000 & 1.000 & 0.455 & 0.172 & 0.231 & 1.000 \\ 0.889 & 0.889 & 0.714 & 0.000 & 0.000 & 0.125 & 0.438 & 0.500 & 0.714 & 0.091 & 0.241 & 0.692 & 0.263 \\ 0.444 & 0.222 & 0.571 & 0.880 & 1.000 & 1.000 & 0.000 & 0.000 & 0.357 & 1.000 & 0.483 & 0.615 & 0.947 \\ 0.222 & 0.333 & 1.000 & 0.560 & 0.688 & 0.625 & 0.750 & 0.286 & 0.500 & 0.364 & 0.207 & 0.769 & 0.474 \\ 0.444 & 0.000 & 0.429 & 0.440 & 0.375 & 0.500 & 0.500 & 0.714 & 0.929 & 0.727 & 0.103 & 1.000 & 0.895 \\ 1.000 & 1.000 & 0.143 & 1.000 & 0.188 & 0.375 & 0.000 & 0.786 & 0.286 & 0.545 & 1.000 & 0.538 & 0.000 \end{bmatrix}.$$

According to formulas (6) to (10), the weights of each second-level indicator were as shown in Table 4.

4.2 | Extension matter-element model of evaluation of green building

The evaluation's degrees of success were divided into five categories:

1. *Completely successful*: The objectives of the project have been fully realized or exceeded; in terms of cost, the project has achieved significant benefits and impacts.
2. *Generally successful*: Most of the projects' objectives have been achieved; in terms of cost, the project has achieved the expected benefits and impact.
3. *Partially successful*: The project has achieved some of the original objectives; in terms of cost, the project has only achieved certain benefits and impact.
4. *Unsuccessful*: The goals achieved by the project have been very limited; in terms of cost, the project has had little positive benefit and impact.

TABLE 4 Weight table of second-level indicators

Serial number	Index system		Entropy E_j	Weight W_j
1	Financial evaluation β_1 (0.210)	Payback period δ_{11}	0.815	0.081
2		Cost saving rate δ_{12}	0.864	0.060
3		Rate of return on investment δ_{13}	0.843	0.069
4	Social impact evaluation β_2 (0.193)	User satisfaction δ_{21}	0.804	0.086
5		External influence δ_{22}	0.756	0.107
6	Building function evaluation β_3 (0.293)	Green compliance δ_{31}	0.855	0.064
7		Land utilization δ_{32}	0.891	0.048
8		Energy conservation and emission reduction δ_{33}	0.887	0.050
9		Material saving and water saving capacity δ_{34}	0.872	0.060
10		Indoor environmental quality δ_{35}	0.838	0.071
11	Operation management evaluation β_4 (0.304)	Management regulation δ_{41}	0.770	0.101
12		Technical management δ_{42}	0.883	0.052
13		Environmental management δ_{43}	0.658	0.151
Total				1.000

5. *Failure*: The goal of the project was unrealistic and could not be achieved; the project had to be terminated in terms of cost.

For the purposes of this article, “unsuccessful” and “failure” were classified at the same level, and the evaluation indicators divided into four levels: level I (completely successful), level II (generally successful), level III (partially successful), and level IV (unsuccessful). On this basis, the classic domain and the joint domain of the green building's success evaluation index were determined as follows:

$$R_{11} = \begin{bmatrix} N_{11} & C_{11} & <80,100> \\ & C_{12} & <80,100> \\ & C_{13} & <80,100> \end{bmatrix}, R_{12} = \begin{bmatrix} N_{12} & C_{11} & <70,80> \\ & C_{12} & <70,80> \\ & C_{13} & <70,80> \end{bmatrix}$$

$$R_{13} = \begin{bmatrix} N_{13} & C_{11} & <60,70> \\ & C_{12} & <60,70> \\ & C_{13} & <60,70> \end{bmatrix}, R_{14} = \begin{bmatrix} N_{14} & C_{11} & <0,60> \\ & C_{12} & <0,60> \\ & C_{13} & <0,60> \end{bmatrix}$$

$$R_{1p} = \begin{bmatrix} N_{1p} & C_{11} & <0,100> \\ & C_{12} & <0,100> \\ & C_{13} & <0,100> \end{bmatrix}.$$

Similarly, the classic domains and joint domains of the other three first-level evaluation indexes were obtained.

According to seven experts' scores on the green building success evaluation index system, the matter-element matrix to be evaluated was:

$$R_1 = \begin{bmatrix} N_1 & C_{11} & 68.00 \\ & C_{12} & 69.71 \\ & C_{13} & 69.14 \end{bmatrix}, R_2 = \begin{bmatrix} N_2 & C_{21} & 79.43 \\ & C_{22} & 80.43 \end{bmatrix}$$

$$R_3 = \begin{bmatrix} N_3 & C_{31} & 79.14 \\ & C_{32} & 80.29 \\ & C_{33} & 79.71 \\ & C_{34} & 78.57 \\ & C_{35} & 77.00 \end{bmatrix}, R_4 = \begin{bmatrix} N_4 & C_{41} & 70.14 \\ & C_{42} & 77.14 \\ & C_{43} & 81.57 \end{bmatrix}.$$

The correlation matrix was established, and the correlation degree of each second-level index with respect to each evaluation level was calculated by formula (10), as follows:

$$F_k(V_{1m}) = \begin{bmatrix} -0.2727 & -0.0588 & 0.0200 & -0.2000 \\ -0.2433 & -0.0090 & 0.0029 & -0.2328 \\ -0.2534 & -0.0262 & 0.0086 & -0.2222 \end{bmatrix}$$

$$F_k(V_{2m}) = \begin{bmatrix} -0.175 & 0.0057 & -0.2276 & -0.3778 \\ -0.0932 & 0.0329 & -0.2458 & -0.3897 \end{bmatrix}$$

$$F_k(V_{3m}) = \begin{bmatrix} -0.0262 & 0.0086 & -0.2222 & -0.3743 \\ 0.0029 & -0.0090 & -0.2422 & -0.3880 \\ -0.0090 & 0.0029 & -0.2328 & -0.3812 \\ -0.0428 & 0.0143 & -0.2112 & -0.3672 \\ -0.0857 & 0.0300 & -0.1795 & -0.3469 \end{bmatrix}$$

$$F_k(V_{4m}) = \begin{bmatrix} -0.2355 & 0.0014 & -0.0044 & -0.2406 \\ -0.0820 & 0.0286 & -0.1824 & -0.3488 \\ -0.0383 & 0.0129 & -0.2655 & -0.4027 \end{bmatrix}.$$

Multiply the vector formed by the weight W_j of the second-level index calculated by the entropy method with the correlation matrix $F_k(V_{nm})$ of the second-level index with respect to each evaluation level in order to obtain the correlation matrix $F_k(V_n)$ of each first-level index, with respect to each evaluation level. The calculation result was as follows:

$$F_k(V_n) = \begin{bmatrix} -0.0542 & -0.0071 & 0.0024 & -0.0455 \\ -0.0102 & 0.0036 & -0.0438 & -0.0710 \\ -0.0106 & 0.0033 & -0.0629 & -0.1083 \\ -0.0339 & 0.0036 & -0.0500 & -0.1032 \end{bmatrix}.$$

According to the calculated weight vector of the first-level index and the correlation degree matrix $F_k(V_n)$ of each first-level index for each evaluation level, the correlation matrix $F_k(V)$ of the object to be evaluated with respect to each evaluation level was determined, and the results of the green building success evaluation could be obtained. The subsequent calculation results were as follows:

$$F_k(V) = \begin{bmatrix} -0.0268 & 0.0012 & -0.0416 & -0.0864 \end{bmatrix}.$$

As can be seen from formula (12), $F_2(V) = 0.0012$, and the degree of success of this green building could be determined. According to the previously set success level categories, this green building's degree of success emerged as at level II, that is, the “generally successful” level, indicating that most of the project objectives had been achieved; in terms of cost, the project achieved the expected benefits and impact.

In addition, according to $F_k(V_n)$, it could be determined that each first-level indicator, including the financial evaluation, social impact evaluation, building function evaluation, and operation management evaluation, respectively, lay at level III, level II, level II, and level II. It can be seen that although the overall management level is good, there are some deficiencies in management. For example, while the financial evaluation was set at level III, there are still some shortcomings compared with the other three aspects. In the process of operation and management of green building projects, these factors should be focused and analyzed mainly in order to enhance the success of the project and reduce the obstacles to the development of green buildings. In addition, the factors affecting the green building's success in terms of the second-level indicators could be identified, and corresponding measures recommended to address the inadequacies found, with the hope that these findings will contribute to a more scientific and rational life cycle management of green buildings.

5 | CONCLUSION

Scientific and effective evaluation on the degree of success of green building projects is an important part for the effective advancement and sustainable development of green building projects. Many factors that are varied and complex affect the degree of success of green building projects, such as technical factors, economic factors, social factors, and environmental factors. Therefore, a reasonable evaluation on the degree of success of green building projects that considers multiple attributes needs to be performed, which can provide theoretical support for the sustainable and healthy development of green building projects.

This article applied the extension matter-element theory and entropy method to establish an evaluation index system of the success of a green building. The study also constructed an extension matter-element model based on the four dimensions of financial evaluation, social impact evaluation, building function evaluation, and operation management evaluation, in order to evaluate the green building's degree of success. Compared with other method, the matter-element analysis method in the degree of success of green building projects has outstanding advantages. This method was deemed fully able to reflect the reality of the whole life cycle of the green building. Moreover, as well as being flexible in terms of operation and convenient to calculate, the method enabled the evaluation results to be expressed in quantitative values, thus objectively reflecting the building's level of success. It can not only make the overall assessment on the degree of success of green building projects accurately but also evaluate each factor separately. Thus, it can find out the contribution rate of each factor separately to the overall in order to take targeted improvement measures. By applying the model to an example of a green building with a one-star design evaluation label in Nanchang City, Jiangxi Province, the suitability of the method in terms of evaluating the success of a green building was reflected, as well as its capacity accurately to discern the level of success and the subordinate degree of each individual index to the evaluation level. The theoretical analysis and case application of this study show that the extension matter-element model can effectively solve the incompatibility problem between individual indicators in a multidimensional index evaluation system and can flexibly select the appropriate membership function according to the data of the evaluation area. The entropy method was employed in the study to calculate the weight, makes full use of the information utility value reflected by the measured data, determines the entropy weight through the degree of variation of the data, avoids the interference of human factors, and enables the evaluation to be more objective.

6 | LIMITATIONS AND FUTURE WORK

In this article, the evaluation of green building success degree is studied at a shallow level, and the extension matter-element theory model of green building success degree evaluation is established. On this basis, the case evaluation is carried out, and the article has achieved some research results. Meanwhile, limitations also exist in this research, and there are still some other issues that need further research and improvement:

1. The article has made some improvements to China's green building evaluation index system. However, due to the limitations of its own investigation and the complexity of the indicators themselves, some factors may be omitted from the index system proposed in this article, for example, the benefit analysis of evaluating the degree of success of a green building. Therefore, the selection of indicators and the establishment of indicator systems in this article need to be further tested and improved.
2. In order to minimize subjectivity, this article uses the entropy method to determine the weight of indicators. The selected entropy weight method needs to be compared with other weight determination methods to further reveal its advantages in more practical applications. In the future, some comprehensive evaluation methods can be used, such as introducing other evaluation methods to further revise the entropy method to determine the index weight more scientifically and accurately.
3. This article only evaluates a specific project and does not select multiple samples for comprehensive evaluation. It is impossible to evaluate and analyze the overall development of green buildings. In the future, it may be necessary to select green building projects throughout the city or the entire province to conduct research from the allover perspective.

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