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Article

Triangular Fuzzy QFD–MCDM Combination Approach for Green Building Design Scheme Evaluation

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Abstract: The integration of green design into building construction is a necessary process in today's world to address environmental issues and achieve sustainable development. However, when evaluating green building design schemes, various factors are intertwined with a high degree of complexity and uncertainty. To realise rational decision-making about green building design schemes, this paper first adopts the mixed techniques of triangular fuzzy numbers, quality function deployment, and Best–Worst Method. It aims to analyse the complex factor relationship between customer needs and green building design technical features and to solve the optimal green building design index weight allocation. Next, a hybrid fuzzy multi-criteria decision-making (MCDM) method integrating triangular fuzzy numbers, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, and Grey Correlation (GC) are proposed to evaluate green building design scheme performance. Finally, an example of a green design project for a hotel building is selected for application validation and analysis in comparison with the existing Complex Proportional Assessment, VlseKriterijuska Optimizacija I Komoromisno Resenje, and DEMATEL-ANP methods. These analyses demonstrate the stability and validity of the results, as well as the rationality and practicability of the proposed triangular fuzzy QFD–MCDM method. This research is a guide to the problem of evaluating green building design schemes.

Keywords: green building; design scheme evaluation; triangular fuzzy numbers; quality function deployment; hybrid MCDM

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1. Introduction

Industry 5.0 states that development in various fields should be centred on human well-being and sustainable development based on environmental protection [1]. However, the current human consumption of natural resources is much faster than the existing regeneration rate of the earth [2], particularly in the building industry, where buildings already accommodate the highest percentage of material resources in our history [3,4], and where traditional building design models cause significant pollution and waste [5]. Green design emphasises the environmental attributes of buildings across their entire life cycle [6]. This ensures efficient utilisation of energy and material resources, reduces the impact on the environment [7], and is in line with the theme of sustainability and the urgent need for environmental protection in today's world [8,9].

Green design schemes need to take into account many factors, such as detachability, recyclability, maintainability, and customer needs [10–12]. This leads to complexity, uncertainty, and ambiguity in their evaluation and selection [13]. Scientifically evaluating and planning design schemes with different foci from multiple perspectives is the key to green design [14,15]. Currently, many scholars are conducting research in the areas of energy, environment, supply chain management, manufacturing, land use management, and other areas of sustainable development in conjunction with the multi-criteria decision-making (MCDM) approach [16–18]. Zhang et al. [19] proposed a hybrid approach combining the Decision-Making Trial and Evaluation Laboratory (DEMATEL), Analytic Network Process (ANP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Grey Relational Analysis (GRA) to select the desired optimal sustainable green materials. Van Thanh et al. [20] developed a hybrid spherical fuzzy AHP and TOPSIS decision-making model for solving the sustainable energy selection problem. Tian et al. [21] proposed a hybrid Analytical Hierarchy Process (AHP), Grey Correlation (GC), and TOPSIS method for the evaluation of the performance of green design schemes. Zarbakhshnia et al. [22] proposed a hybrid approach of Fuzzy AHP and grey multiobjective optimisation by ratio analysis (MOORA-G) for the evaluation and selection of green logistics providers. Chandra et al. [23] used a hybrid Stepwise Weight Assessment Ratio Analysis (SWARA) and Complex Proportional Assessment (COPRAS) approach and evaluated and ranked four types of additive manufacturing processes in terms of environmental issues and sustainability. Sathiya et al. [24] researched green robot design and evaluation as an MCDM problem and proposed a decision-making approach that combines Interpretive Structural Modelling and ANP. Rahman et al. [25] proposed a GIS-based AHP method for optimising sustainable urban land use schemes.

In recent years, the interest of scholars in the areas of green building design decision-making has been increasing and MCDM has gradually become one of the widely used tools in this area [26]. Falqi et al. [27] conducted siliceous material management by employing the fuzzy TOPSIS method to design sustainable concrete buildings. Hashemkhani Zolfani et al. [28] proposed the multi-criteria decision model combining SWARA and COPRAS for the evaluation of the environmental sustainability of hotel construction projects. Liu et al. [29] proposed an ANP method based on DEMATEL and Best–Worst Method (BWM) for prioritising green building indicators. Abdel-Basset et al. [30] used Delphi and AHP methods to evaluate and rank the dimensions and indicators of green buildings. Yan et al. [31] used DEMATEL-based ANP (DANP) and VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) methods to identify problems and generate improvement factors in the evaluation of green building systems. Caballero Moreno et al. [32] proposed a MIVES-based decision-making method for the evaluation of the sustainability of floor slabs.

In recent years, as market competition has intensified and the resource environment continues to deteriorate, the concerns of governments, businesses, and customers are changing over time. Customers' ecological awareness is increasing, so enterprises will improve customer satisfaction by focusing on green design, based on customer-driven green design methods gradually appearing in people's vision. Quality function deployment (QFD) is a widely used methodology in product design that helps teams correlate customer needs with design features to ensure that products designed and produced respond more effectively to customer expectations. QFD in combination with MCDM identifies and weights various quality metrics to better measure scheme quality, which in turn helps to improve the design. The application of MCDM techniques to enhance QFD analysis performance has emerged as a cutting-edge research approach in recent years [33,34]. Wang et al. [35] proposed an enhanced QFD method for ranking the technical attributes of compressors by combining cloud modelling and GRA. Hsu et al. [33] proposed a QFD-based Fuzzy Delphi, AHP, DEMATEL, and GRA integration for decision-making in electronics manufacturing. He et al. [36] developed a Kano–DEMATEL–QFD hybrid approach for optimising risk-resilient solutions for sustainable supply chains. Al-Mendwi and Doos [37] proposed a hybrid approach combining AHP, QFD, and extended PROMETHEE II methods to solve the problem of decision-making on a welding scheme for large engineering.

Summarising the above literature, the MCDM method has shown its superiority in different areas of sustainable development engineering, and the attention it has received in the new field of green building design has been increasing. The evaluation of green building design is closely related to the realisation of sustainable social development in the future [38,39], so further research on the MCDM method in this area is particularly necessary. Reasonable use of QFD can effectively decrease development costs and enhance design quality and customer satisfaction [40]. There is good complementarity between the QFD and MCDM methods, and combining QFD with fuzzy logic and other MCDM methods can provide a more encompassing and integrated guide to the green building design process. This helps to better meet diverse needs and multiple objectives, improve building quality, reduce risk, and support more effective decision-making. Based on the research status quo summarised above, this paper takes customer satisfaction as the guide in the process of building innovation and design, with green performance evaluation and reasonable and effective allocation of resources as the goal to investigate the green performance evaluation of buildings and optimisation of resource allocation based on customer satisfaction. Compared with the existing research, this present study makes three significant contributions:

(1) Based on the research and expert evaluation data, the QFD model is applied to evaluate the factors affecting the green performance of the building, and the triangular fuzzy QFD and BWM hybrid green design index weight evaluation method is proposed.
(2) Considering the uncertainty of the scoring of scheme experts, the hybrid MCDM method of triangular fuzzy numbers, TOPSIS, and GC fusion is applied to realise the selection of optimal schemes for the green design of buildings.
(3) The green design of a hotel is used as an application example to validate the above-proposed method. The efficiency of the hybrid triangular fuzzy numbers, TOPSIS, and GC decision-making method is demonstrated by comparing it with other classical methods.

Structure and content of the paper: in Section 2, a comprehensive evaluation system for green design schemes is first constructed, followed by a description of several methods used and proposed. In Section 3, the models and approach proposed in this paper are case-analysed using the hotel as the research object and compared with other classical methods. Section 4 summarises the conclusions and further research topics.

2. Evaluation Approach

This section presents the proposed hybrid algorithm. First, we build a comprehensive evaluation system for green building design schemes. Then, the triangular fuzzy QFD and BWM weight calculation method is described. Finally, a triangular fuzzy TOPSIS and GG hybrid method is proposed.

2.1. Construction of a Comprehensive Evaluation System of Green Design Schemes

A reasonable evaluation indicator system needs to comprehensively reflect the main factors affecting green building design. In general, the more comprehensive the indicator system is, the more objective and rational the decision-making results will be. However, too many indicators can complicate the evaluation process and create a waste of resources. Therefore, the number of indicators to be selected should be kept within a reasonable range, and the selection should be rationalised according to the degree to which each indicator's role is within an evaluation of green design schemes. Keeney et al. [41] pointed out five basic properties of completeness, operability, decomposability, nonredundancy, and size that need to be fulfilled to establish a relevant system of evaluation metrics when dealing with decision-making problems. On the premise of observing the above basic nature, the principles of systematicity, typicality, dynamism, ease of operation, and integrity should also be taken into account when building the evaluation index system. According to the above principles and the existing literature [42–44], this paper constructs the following evaluation index system to choose the green building design scheme. The constructed system consists of four first-level indicators and nine second-level indicators, and the selected first-level indicators are described below:

(1) Environmental benefits

Each stage within a building's life cycle has some impact on the environment, but the key is in the design and development phase. In the long run, if we only consider its building quality and building cost without considering whether its design and construction process causes pollution and harm to the environment, it will not only cause enormous losses to enterprises but also cause irreparable losses and disasters to the natural society [44,45]. Therefore, it is necessary to introduce the environmental benefit factor into the evaluation system of the green design scheme selection index and select the green building design schemes that can be better harmonised with the environment.

(2) Energy consumption

Reducing energy wastage produced during the building design and construction process is an important issue to be considered at present. Only by minimising energy wastage and implementing concepts of energy conservation and reduction through the selection of design schemes can it meet the requirements of the current era of development and enhance its application value.

(3) Resource utilisation

Resource utilisation should be maximised in the building design and construction process. Unreasonable resource utilisation will further accelerate the shortage of resources, exacerbate secondary pollution, and enhance enterprise costs. Therefore, in the process of constructing the evaluation system of the green building design scheme selection index, it is necessary to consider the resource utilisation index in its evaluation system.

(4) Economic benefits

Building development and design is the key to enterprise development and social progress. Good economic benefits can promote the benign development of enterprises and society [43]. A good building design should not only look at the building's appearance and building performance but also consider the overall cost of the building and the economic benefits it brings, which is very important to both the enterprise and society [46].

According to the above research and analyses, the case evaluation index system as shown in Figure 1 is constructed.

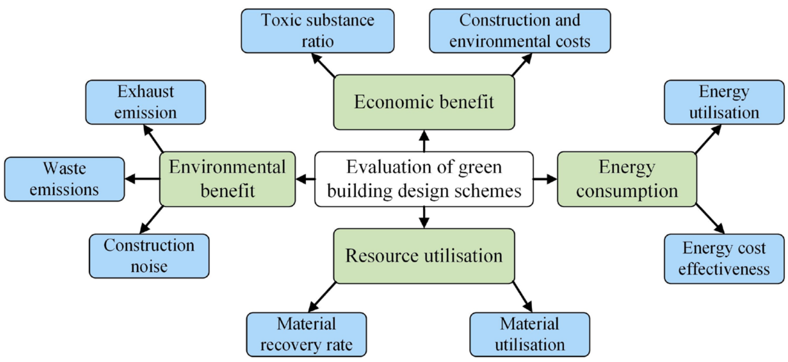

Figure 1. Evaluation index system for green building design scheme.

2.2. Triangular Fuzzy QFD–BWM Indicator Weight Evaluation Method

2.2.1. Triangular Fuzzy Numbers

Fuzzy set theory has made advances in many disciplines and fields, effectively overcoming the ambiguity and uncertainty of the environment in engineering research. The triangular fuzzy numbers method is the most popular fuzzy number method [47]. To better demonstrate the triangular fuzzy BWM method, one needs to understand the definition of triangular fuzzy numbers.

Definition 1. *$\widetilde{S} = (s_1, s_2, s_3)$ can be referred to as a triangular fuzzy number with respect to $\widetilde{S}$, $s1,\ s2,\ s3 \in R\ (s1 \leq s2 \leq s3)$, whose affiliation function is shown in Equation (1):*

$$\mu\widetilde{S}(s) = \begin{cases} \frac{s-s_1}{s_2-s_1} & \text{if} \quad s_1 \leq s \leq s_2 \\ \frac{s_3-s}{s_3-s_2} & \text{if} \quad s_2 \leq s \leq s_3 \\ 0 & \text{if} \quad s < s_1 \text{ or } s \geq s_3 \end{cases} \tag{1}$$

where s_1 is the upper limit value of $\widetilde{S}$, s_2 is the median value of $\widetilde{S}$, and s_3 is the lower limit value of $\widetilde{S}$. When $s_1 = s_2 = s_3$, the triangular fuzzy number $\widetilde{S}$ is converted from a triangular fuzzy number to a usual positive real number. When two triangular fuzzy numbers $\widetilde{S} = (s_1, s_2, s_3)$ and $\widetilde{Z} = (z_1, z_2, z_3)$ satisfy $s_1 = z_1$, $s_2 = z_2$, and $s_3 = z_3$, the two triangular fuzzy numbers can be said to be equal, that is, $\widetilde{S} = \widetilde{Z}$.

The following arithmetic rule exists for any two triangular fuzzy numbers $\widetilde{S} = (s_1, s_2, s_3)$ and $\widetilde{Z} = (z_1, z_2, z_3)$:

(1) Addition rules:

$$\widetilde{S} + \widetilde{Z} = (s_1, s_2, s_3) + (z_1, z_2, z_3) = (s_1 + z_1, s_2 + z_2, s_3 + z_3) \tag{2}$$

(2) Multiplication rules:

$$\widetilde{S}\widetilde{Z} = (s_1 z_1, s_2 z_2, s_3 z_3) \tag{3}$$

when any triangular fuzzy number is multiplied by a real number W:

$$W\widetilde{S} = (Ws_1, Ws_2, Ws_3) \tag{4}$$

(3) Division rules:

$$\frac{\widetilde{S}}{\widetilde{Z}} = \left(\frac{s_1}{z_1}, \frac{s_2}{z_2}, \frac{s_3}{s_3}\right), \frac{1}{\widetilde{z}} = \left(\frac{1}{z_1}, \frac{1}{z_2}, \frac{1}{z_3}\right) \tag{5}$$

Triangular fuzzy numbers need to be compared using the concept of possibility degree in their application process, and the definition of possibility degree between triangular fuzzy numbers is given below:

Definition 2. *The possibility degree of any two triangular fuzzy numbers $\widetilde{S} = (s_1, s_2, s_3)$ with $\widetilde{Z} = (z_1, z_2, z_3)$, $\widetilde{S} \geq \widetilde{Z}$ is calculated using Equation (6):*

$$\rho(\widetilde{S} \geq \widetilde{Z}) = \lambda \max\left\{1 - \max\left(\frac{z_2 - s_1}{s_2 - s_1 + z_2 - z_1}, 0\right), 0\right\} + (1 - \lambda)\max\left\{1 - \max\left(\frac{z_3 - s_2}{s_3 - s_2 + z_3 - z_2}, 0\right), 0\right\} \tag{6}$$

where $\lambda \in [0, 1]$ and λ depend on the decision-maker's degree of preference for risk.When the decision-maker's attitude toward risk is preference-seeking, $\lambda > 0.5$; when the decision-maker's attitude toward risk is neutral, $\lambda = 0.5$; and when the decision-maker's attitude toward risk is pessimistic, $\lambda < 0.5$.

According to the above definitions, conclusions can be justified as follows:

Suppose any two triangular fuzzy numbers $\widetilde{S} = (s_1, s_2, s_3)$ and $\widetilde{Z} = (z_1, z_2, z_3)$. Then:

$$0 \leq \rho(\widetilde{S} \geq \widetilde{Z}) \leq 1 \tag{7}$$

$$\rho(\widetilde{S} \geq \widetilde{Z}) = \begin{cases} 1 & \text{if} \quad z_3 \leq s_1 \\ 0 & \text{if} \quad s_3 \leq z_1 \\ 0.5 & \text{if} \quad \rho(\widetilde{S} \geq \widetilde{Z}) + \rho(\widetilde{Z} \geq \widetilde{S}) = 1 \end{cases} \tag{8}$$

In particular, if there exist h triangular fuzzy numbers to compare between, then the resulting possibility degree matrix $\rho = (\rho_{\text{ij}})_{h \times h}$ belongs to the fuzzy complementary judgment matrix.

The formula for the distance between two triangular fuzzy numbers is given below:

Definition 3. *Any two triangular fuzzy numbers $\widetilde{S} = (s_1, s_2, s_3)$ and $\widetilde{Z} = (z_1, z_2, z_3)$ whose distance formula can be expressed as:*

$$D(\widetilde{S}, \widetilde{Z}) = \sqrt{\frac{1}{3}\left[(s_1 - z_1)^2 + (s_2 - z_2)^2 + (s_3 - z_3)^2\right]} \tag{9}$$

2.2.2. BWM Method

The BWM is a typical MCDM method used to help decision-makers choose between multiple schemes or options [48]. The BWM is able to reduce the burden on decision-makers through fewer two-by-two comparisons than methods such as AHP [49]. This feature simplifies preference cues from decision-makers and leads to more consistent results. As a result, BWM is often applied to MCDM issues, involving but not limited to algorithm evaluation, transportation and logistics, supply chain management, technical acceptance, risk management, and energy [50,51]. In green building design research, the BWM method is more effective in dealing with a subjective evaluation and determining relative weights than other methods [52], and its combination with triangular fuzzy numbers and QFD is able to consider quality and functionality comprehensively, which significantly improves the scientificity and objectivity of decision-making [53]. The main steps of BWM are as follows:

Step 1: Establish a system of indicators that integrates multiple considerations and identify, through senior experts, the best and worst indicators a_B and a_W.

Step 2: Determine the best-other and other-worst comparison vectors by means of expert scoring, denoted as $a_{Bj} = [a_{B1}, a_{B2}, \ldots, a_{Bm}]$ and $a_{jW} = [a_{1W}, a_{2W}, \ldots, a_{mW}]$, respectively, in the manner shown in Figure 2.

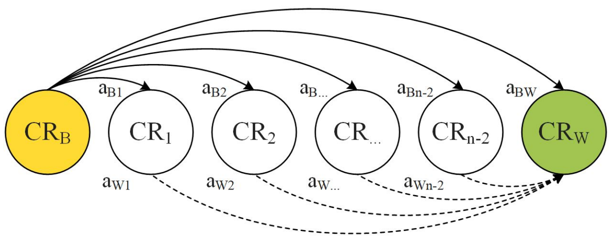

Figure 2. BWM comparison method.

Step 3: Based on the comparison vectors, a nonlinear planning model is developed as shown in Equation (10).

$$\begin{gathered} \min_{\xi,\omega} \xi \\ s.t. \\ \begin{cases} \left|\frac{\omega_B}{\omega_j} - a_{Bj}\right| \leq \xi \quad \forall j = 1, 2, \ldots, n \\ \left|\frac{\omega_j}{\omega_W} - a_{jW}\right| \leq \xi \quad \forall j = 1, 2, \ldots, n \\ \sum_{j=1}^{n} \omega_j = 1, \omega_j \geq 0 \quad \forall j = 1, 2, \ldots, n \end{cases} \end{gathered} \tag{10}$$

To facilitate understanding the nonlinear planning model of the BWM, an example is given as follows, wherein the nonlinear mathematical planning model is established as seen in Equation (11). The weights obtained after the LINGO calculation are $\omega_1 = 0.0714$, $\omega_2 = 0.3387$, and $\omega_3 = 0.5899$.

$$\min_{\xi,\omega} \xi$$
$$s.t.\ \begin{cases} \left|\frac{\omega_3}{\omega_1} - 8\right| \leq \xi \\ \left|\frac{\omega_3}{\omega_2} - 2\right| \leq \xi \\ \left|\frac{\omega_2}{\omega_1} - 5\right| \leq \xi \\ \omega_1 + \omega_2 + \omega_3 = 1 \quad \omega_1, \omega_2, \omega_3 \geq 0 \end{cases} \tag{11}$$

2.2.3. Triangular Fuzzy BWM Method

Although the BWM method is effective in simplifying the process of decision-making as well as reducing the risk of inconsistency, there is still ambiguity. To better address the uncertainty in decision-making problems and improve the flexibility of decision-making, many scholars have combined the BWM method with fuzzy set theory and successfully applied it to solve many engineering problems [54,55]. Therefore, we combine the two methods in Sections 2.2.1 and 2.2.2 into a triangular fuzzy BWM method, as shown in Equation (12).

$$\min \xi$$
$$s.t.\ \begin{cases} \left|\frac{(s_B^1, s_B^2, s_B^3)}{\left(s_j^1, s_j^2, s_j^3\right)} - \left(s_{Bj}^1, s_{Bj}^2, s_{Bj}^3\right)\right| \leq (\xi^*, \xi^*, \xi^*) \\ \left|\frac{\left(s_j^1, s_j^2, s_j^3\right)}{(s_W^1, s_W^2, s_W^3)} - \left(s_{jW}^1, s_{jW}^2, s_{jW}^3\right)\right| \leq (\xi^*, \xi^*, \xi^*) \\ \sum_{j=1}^{n}\left(\frac{s_j^1 + 4s_j^2 + s_j^3}{6}\right) = 1 \\ 0 \leq s_j^1 \leq s_j^2 \leq s_j^3 \leq 1 \quad \forall j = 1, 2, \ldots, n \\ \xi = \left(s_\xi^1, s_\xi^2, s_\xi^3\right) \quad \xi^* \leq s_\xi^1 \leq s_\xi^2 \leq s_\xi^3 \end{cases} \tag{12}$$

2.2.4. Triangular Fuzzy QFD–BWM Method

During the building design phase, analysing the connection between customer needs with green design technology features to determine the focus direction of green design has become a difficult problem for many manufacturing enterprises. Therefore, this section combines the HOQ, the core tool of QFD, with the triangular fuzzy BWM, which is used to fully analyse the complex fuzzy mapping relationship between customer needs and green design technical features. This section demonstrates the solution process of a hybrid triangular fuzzy QFD–BWM method as follows:

Step 1: Determine the best (most important) customer needs and the worst (least important) customer needs based on the *k*th decision-maker as well as the best-other vector and the others-worst vector.

Step 2: According to the *k*th decision-maker, determine the green design technology features that have the greatest impact and the least impact on customer demand for each customer demand, as well as the best-other and other-worst vectors.

Step 3: The optimal weight (importance) and optimal relevance matrices of the customer requirements are obtained from the QFD–BWM nonlinear solution.

Step 4: Obtain the best weight (importance) of the green design technology features for the *k*th decision-maker.

Step 5: Calculate the combined best weight (importance) of green design technology features for all decision-makers.

The above triangular fuzzy QFD–BWM method can effectively increase customer satisfaction while accelerating the efficiency of design decisions. With the above steps, the influence of subjective factors on green design technology characteristics can be diluted and the accuracy of the actual application results can be improved. The FQFD using fused triangular fuzzy numbers expresses well the numerous fuzzy and stochastic processes that exist in the green design phase (e.g., customers cannot express their inner favorites with accurate numerical values).

2.3. Triangular Fuzzy TOPSIS–GG Scheme Evaluation Method

2.3.1. TOPSIS Method

TOPSIS is a type of MCDM method that performs scheme evaluation by comparing each alternative close to the positive ideal schemes and far from the negative ideal schemes [56]. Schemes that maximise benefits or minimise costs are known as positive ideal schemes, and schemes that maximise costs or minimise benefits are known as negative ideal schemes. The significant advantages of the TOPSIS method in green building design research are its effectiveness in dealing with multi-criteria decision-making problems and its ability to weigh and rank effectively [57]. Combining TOPSIS with triangular fuzzy numbers can further enhance the handling of uncertainties present in green building design, resulting in more accurate and flexible evaluations. The traditional TOPSIS method steps are as follows:

Step 1: The initial decision matrix is constructed based on the evaluation values of each evaluation indicator for each scheme.

$$X = (X_{ij})_{n\times m} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{13}$$

Step 2: Due to the differences in the scale between the individual evaluation indicators, the indicators need to be standardised to form a standardised decision matrix U.

When x_{ij} is a positive indicator (benefit-based indicator), the standardisation method is shown in Equation (14).

$$u_{ij} = \frac{x_{ij}}{\max_i x_{ij}}, \quad (i \in \{1,2,\ldots,n\}\ j \in \{1,2,\ldots,m\}) \tag{14}$$

When x_{ij} is a negative indicator (cost-based indicator), it is normalised as shown in Equation (15).

$$u_{ij} = \frac{\min_i x_{ij}}{x_{ij}}, \quad (i \in \{1,2,\ldots,n\}\ j \in \{1,2,\ldots,m\}) \tag{15}$$

Step 3: The weighted standardised decision matrix F is calculated based on the weights of each indicator.

$$F = \omega^T u = \begin{bmatrix} \omega_1' u_{11} & \omega_2' u_{12} & \cdots & \omega_m' u_{1m} \\ \omega_1' u_{21} & \omega_2' u_{22} & \cdots & \omega_m' u_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \omega_1' u_{n1} & \omega_2' u_{n2} & \cdots & \omega_m' u_{nm} \end{bmatrix} \tag{16}$$

Step 4: Find positive ideal schemes $F^+ = \{F_1^+, F_2^+, \ldots, F_n^+\}$ and negative ideal schemes $F^- = \{F_1^-, F_2^-, \ldots, F_n^-\}$.

$$F_j^+ = \left\{\max_{1\le i\le n}\left(\{F_{ij}\}_{i=1}^n\right)\middle| j \in J^+, \min_{1\le i\le n}\left(\{F_{ij}\}_{i=1}^n\right)\middle| j \in J^-\right\} = \left(F_1^+, F_2^+, \ldots, F_m^+\right) \tag{17}$$

$$F_j^- = \left\{\min_{1\le i\le n}\left(\{F_{ij}\}_{i=1}^n\right)\middle| j \in J^+, \max_{1\le i\le n}\left(\{F_{ii}\}_{i=1}^n\right)\middle| j \in J^-\right\} n = \left(F_1^-, F_2^-, \ldots, F_m^-\right) \tag{18}$$

Step 5: The Euclidean distance between each alternative scheme and the positive and negative ideal schemes is calculated.

$$E_i^+ = \sqrt{\sum_{j=1}^{m} \left[F_{ij} - F_j^+\right]^2}, \qquad (i = 1, 2, \cdots, n) \tag{19}$$

$$E_i^- = \sqrt{\sum_{j=1}^{m} \left[F_{ij} - F_j^-\right]^2}, \qquad (i = 1, 2, \cdots, n) \tag{20}$$

Step 6: The relative closeness of each scheme to the positive ideal schemes is calculated, and the relative closeness is used as a criterion to rank the evaluation of the schemes.

$$G_i = \frac{E_i^-}{E_i^+ + E_i^-}, \ (i = 1, 2, \cdots, n) \tag{21}$$

A larger *Gi* indicates a better scheme.

2.3.2. GC Method

The GC method evaluates schemes by means of grey relational coefficients and uses the grey relational degree of similarity between data series as a measure by analysing the similarity curves and geometric relationships between data series. The traditional GC method steps are as follows:

Step 1: Based on standardised decision matrix F and positive ideal schemes F^+ of the traditional TOPSIS, calculate the grey relational coefficients between the ith alternative scheme and the positive ideal schemes with respect to the *jth* indicator, and the grey relational coefficient matrix R^+ is obtained.

$$R^+ = \begin{bmatrix} r_{11}^+ & r_{12}^+ & \cdots & r_{1m}^+ \\ r_{21}^+ & r_{22}^+ & \cdots & r_{2m}^+ \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1}^+ & r_{n2}^+ & \cdots & r_{nm}^+ \end{bmatrix} \tag{22}$$

r_{ij}^+ is calculated as shown in Equation (23).

$$r_{ij}^+ = \frac{\min_i \min_j \left|F_j^+ - F_{ij}\right| + \updownarrow \max_i \max_j \left|F_j^+ - F_{ij}\right|}{\left|F_j^+ - F_{ij}\right| + \updownarrow \max_i \max_j \left|F_j^+ - F_{ij}\right|} \tag{23}$$

where $\updownarrow$ is expressed as the resolution coefficient, $\updownarrow \in [0, 1]$, and there is a negative correlation between $\updownarrow$ and the correlation coefficient. The smaller $\updownarrow$ is, the greater the difference between the correlation coefficients and the greater the ability to differentiate between schemes because, usually, $\updownarrow$ takes 0.5.

Step 2: The grey relational coefficient between the *ith* alternative and the ideal schemes is calculated:

$$R_i^+ = \frac{1}{m}\sum_{j=1}^{m} r_{ij}^+, (i \in \{1, 2, \ldots, n\}) \tag{24}$$

A larger R_i^+ indicates a better scheme and a higher degree of correlation with the ideal schemes.

2.3.3. Triangular Fuzzy TOPSIS–GC Method

The TOPSIS method evaluates schemes based on the distance relationships between data series, which only reflect the positional relationships between schemes, and the distance as an evaluation criterion does not reflect the changes between data series. For example, when there is a large difference in the indexes of two schemes, there may be an equal distance between the schemes and the ideal schemes. The GC method uses the similarity between two data series as a measure, called the grey relational coefficient, which can be used to evaluate the change in situation between data series. However, using the grey relational coefficient as an evaluation criterion does not reflect the distance between data series. To evaluate schemes objectively and rationally, evaluation cannot be evaluated solely through the use of distances or grey relational coefficients but also through changes in circumstances between data series. In addition, the two methods mentioned above use both precise data values for solving, which decreases the accuracy when encountering fuzzy and uncertain situations. In many cases, decision-makers have difficulty in obtaining accurate information. To be more objective and reasonable for scheme selection, this research fuses the above two methods and introduces the triangular fuzzy number to improve them, which makes up for the lack of poor adaptability of the original method in fuzzy uncertainty. Finally, the triangular fuzzy TOPSIS–GC method is proposed. The specific steps are as follows:

Step 1: Based on the fuzzy evaluation values for each evaluation index of each scheme by each expert, construct the initial fuzzy decision matrix:

$$\widetilde{X} = (\widetilde{X}_{ij})_{n\times m} = \begin{bmatrix} \widetilde{x}_{11} & \widetilde{x}_{12} & \cdots & \widetilde{x}_{1m} \\ \widetilde{x}_{21} & \widetilde{x}_{22} & \cdots & \widetilde{x}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{x}_{n1} & \widetilde{x}_{n2} & \cdots & \widetilde{x}_{nm} \end{bmatrix} \tag{25}$$

In particular, if T experts have evaluated all the evaluation indicators of each scheme, then the fuzzy evaluation value of the *ith* scheme is calculated as:

$$\widetilde{x}_{ij} = \frac{1}{T}\left(\widetilde{x}_{ij}{}^{1} + \widetilde{x}_{ij}{}^{2} + \ldots + \widetilde{x}_{ij}{}^{T}\right) \tag{26}$$

Step 2: Fuzzy standardisation processing, which standardises the fuzzy evaluation value of each evaluation index to eliminate the difference in the scale.

When X_{ij} is a positive indicator (benefit-based indicator), it is standardised as follows:

$$\widetilde{u_{ij}} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), \text{ and } c_j^* = \max c_{ij} \tag{27}$$

When X_{ij} is a negative indicator (cost-based indicator), the normalisation method is:

$$\widetilde{u_{ij}} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \text{ and } a_j^- = \min a_{ij} \tag{28}$$

where a, b, and c are the triangular fuzzy numbers for the evaluation of each indicator for each evaluation scheme.

The fuzzy standardised decision matrix $\widetilde{U}$ is obtained after the standardisation is completed:

$$\widetilde{U} = \begin{bmatrix} \widetilde{u}_{11} & \widetilde{u}_{12} & \ldots & \widetilde{u}_{1m} \\ \widetilde{u}_{21} & \widetilde{u}_{22} & \ldots & \widetilde{u}_{2m} \\ \vdots & \vdots & \ldots & \vdots \\ \widetilde{u}_{n1} & \widetilde{u}_{n2} & \ldots & \widetilde{u}_{nm} \end{bmatrix} \tag{29}$$

Step 3: Calculate the fuzzy weighted standardised decision matrix $\widetilde{F}$ based on the weights of each indicator.

$$\widetilde{F} = \omega^T \widetilde{u} = \begin{bmatrix} \omega_1' \widetilde{u}_{11} & \omega_2' \widetilde{u}_{12} & \cdots & \omega_m' \widetilde{u}_{1m} \\ \omega_1' \widetilde{u}_{21} & \omega_2' \widetilde{u}_{22} & \cdots & \omega_m' \widetilde{u}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \omega_1' \widetilde{u}_{n1} & \omega_2' \widetilde{u}_{n2} & \cdots & \omega_m' \widetilde{u}_{nm} \end{bmatrix} \tag{30}$$

Step 4: Determine the fuzzy positive ideal schemes $\widetilde{F^+}$ and fuzzy negative ideal schemes $\widetilde{F^-}$ for the fuzzy TOPSIS method.

$$\widetilde{F_j^+} = \left\{ \max_{1 \le i \le n} \left(\left\{ \widetilde{F_{ij}} \right\}_{i=1}^n \right) \middle| j \in J^+, \min_{1 \le i \le n} \left(\left\{ \widetilde{F_{ij}} \right\}_{i=1}^n \right) \middle| j \in J^- \right\} = \left(\widetilde{F_1^+}, \widetilde{F_2^+}, \ldots, \widetilde{F_m^+} \right) \tag{31}$$

$$\widetilde{F_j^-} = \left\{ \min_{1 \le i \le n} \left(\left\{ \widetilde{F_{ij}} \right\}_{i=1}^n \right) \middle| j \in J^+, \max_{1 \le i \le n} \left(\left\{ \widetilde{F_{ii}} \right\}_{i=1}^n \right) \middle| j \in J^- \right\} n = \left(\widetilde{F_1^-}, \widetilde{F_2^-}, \ldots, \widetilde{F_m^-} \right) \tag{32}$$

Step 5: The Euclidean distance between each alternative scheme and the fuzzy positive and negative ideal schemes is calculated as shown in Equations (33) and (34).

$$E_i^+ = \sum_{j=1}^m D\left(\widetilde{F}_{ij}, \widetilde{F_j^+} \right) \quad i = 1, 2, \cdots n \tag{33}$$

$$E_i^- = \sum_{j=1}^m D\left(\widetilde{F}_{ij}, \widetilde{F_j^-} \right) \quad i = 1, 2, \cdots n \tag{34}$$

Step 6: The fuzzy relative closeness of each alternative scheme to the fuzzy positive ideal schemes is calculated, and the fuzzy relative closeness is used as a criterion to rank the evaluation of the alternatives.

$$G_i = \frac{E_i^-}{E_i^+ + E_i^-}, \quad (i = 1, 2, \cdots, n) \tag{35}$$

The larger G_i is, the closer the scheme is to the fuzzy positive ideal schemes, and the further it is from the fuzzy negative ideal schemes, the better the scheme is.

Step 7: Calculate the fuzzy GC method distance matrix B based on the fuzzy weighted normalised decision matrix F from Step 3 and the fuzzy positive ideal schemes F^+ from Step 4, again using Equation (36).

$$B = \begin{bmatrix} D\left(\widetilde{F}_{11}, \widetilde{F_1^+} \right) & D\left(\widetilde{F}_{12}, \widetilde{F_2^+} \right) & \cdots & D\left(\widetilde{F}_{1m}, \widetilde{F_m^+} \right) \\ D\left(\widetilde{F}_{21}, \widetilde{F_1^+} \right) & D\left(\widetilde{F}_{22}, \widetilde{F_2^+} \right) & \cdots & D\left(\widetilde{F_{1m}}, \widetilde{F_m^+} \right) \\ \vdots & \vdots & \ddots & \vdots \\ D\left(\widetilde{F}_{n1}, \widetilde{F_1^+} \right) & D\left(\widetilde{F}_{n2}, \widetilde{F_1^+} \right) & \cdots & D\left(\widetilde{F}_{nm}, \widetilde{F_m^+} \right) \end{bmatrix} \tag{36}$$

Step 8: Calculate the grey relational coefficient matrix R^+ based on the distance matrix B.

$$R^+ = \begin{bmatrix} r_{11}^+ & r_{12}^+ & \cdots & r_{1m}^+ \\ r_{21}^+ & r_{22}^+ & \cdots & r_{2m}^+ \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1}^+ & r_{n2}^+ & \cdots & r_{nm}^+ \end{bmatrix} \tag{37}$$

In particular, among others:

$$r_{ij}^+ = \frac{\min_i \min_j \left(D\left(\widetilde{F}_{nm}, \widetilde{F_m^+} \right) \right) + \updownarrow \max_i \max_j \left(D\left(\widetilde{F}_{nm}, \widetilde{F_m^+} \right) \right)}{D\left(\widetilde{F}_{nm}, \widetilde{F_m^+} \right) + \updownarrow \max_i \max_j \left(D\left(\widetilde{F}_{nm}, \widetilde{F_m^+} \right) \right)} \tag{38}$$

Step 9: Calculate the fuzzy grey relational coefficients between each alternative scheme and the fuzzy positive ideal schemes

$$R_i^+ = \frac{1}{m}\sum_{j=1}^{m} r_{ij}^+, (i \in \{1,2,\ldots,n\}) \tag{39}$$

A larger R_i^+ indicates a better scheme and a higher degree of correlation with the fuzzy positive ideal schemes.

Step 10: To avoid subjectivity and irrationality, based on the fuzzy grey relational coefficient and fuzzy relative closeness, calculate the comprehensive closeness index ZS_i of each scheme by using the nonlinear programming method. Assuming that these two indexes have the same weight, ZS_i is calculated as follows:

$$\begin{gathered} \min z = \sum_{i=1}^{n}\left[(ZS_i - R_i)^2 + (ZS_i - G_i)^2\right] \\ (i \in \{1,2,\ldots,n\}) \end{gathered} \tag{40}$$

where $\min(R_i, G_i) \le ZS_i \le \max(R_i, G_i)$, the larger the ZS_i, the better the scheme.

Figure 3 shows the main flow of the hybrid approach proposed in this section.

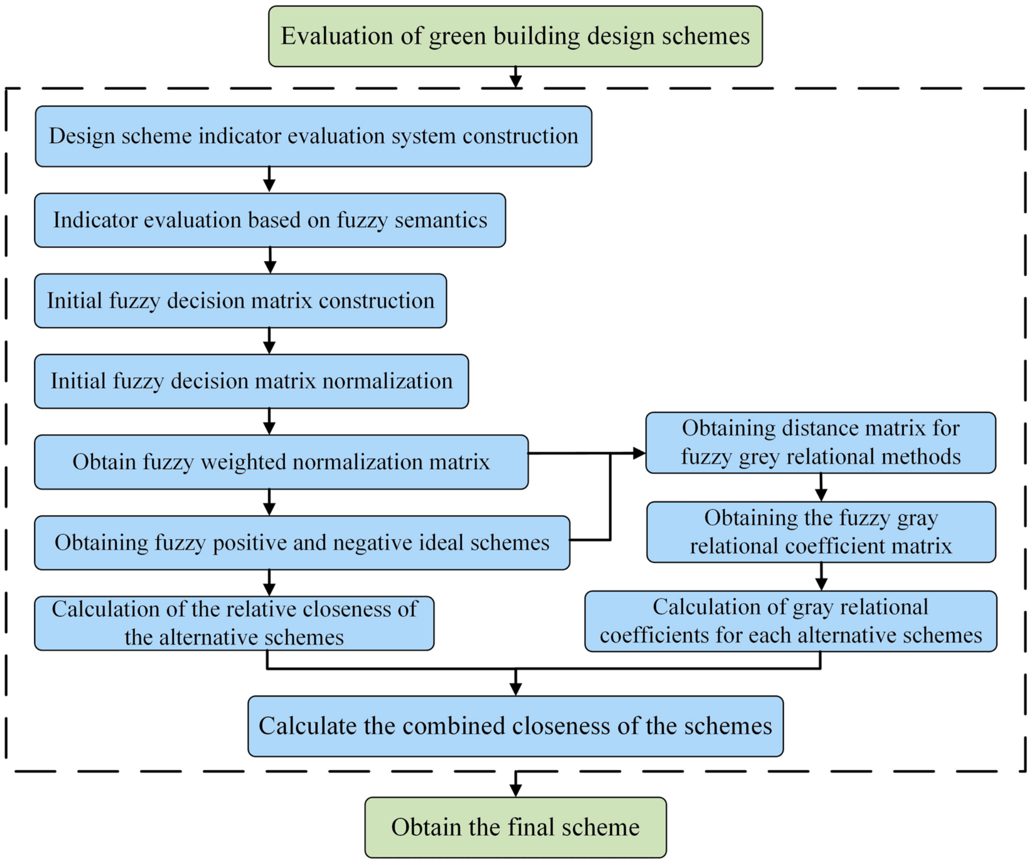

Figure 3. Triangular fuzzy TOPSIS–GC flowchart.

3. Evaluation Example

3.1. Validation of the Triangular Fuzzy QFD–BWM Green Design Index Weights Solving Method

To verify the convenience and suitability of the triangular fuzzy QFD–BWM green design index weight distribution, this paper takes the green design project of a hotel building as an example. The project is initiated on the basis of a project commissioned by a private investor in Beijing, China. The city of Beijing faces serious environmental challenges due to pollution problems and escalating construction activities, while municipal policies are increasingly focused on environmental sustainability. In this context, environmental sustainability has become a crucial consideration in the city's construction sector [58]. Therefore, the main objective of the project was to develop an environmentally sustainable hotel building design scheme based on an evaluation of the needs of the customer. According to the evaluation system of green design schemes developed in Section 2.1, the first-level indicators are denoted as CR1~CR4 and the second-level indicators are denoted as DT1~DT9, as shown in Table 1. At the same time, three senior experts in the industry are invited to construct HOVs based on QFD rules, triangular fuzzy linguistic levels (as shown in Table 2), and their knowledge structure and obtain the green design index assignment according to the QFD–BWM analysis method.

Table 1. Green building design evaluation index system.

First-Level Indicators	Second-Level Indicators
CR1: Environmental benefit	DT1: Exhaust emission DT2: Waste emissions DT3: Construction noise
CR2: Energy consumption	DT4: Energy utilisation DT5: Energy cost effectiveness
CR3: Resource utilisation	DT6: Material utilisation DT7: Material recovery rate
CR4: Economic benefit	DT8: Toxic substance ratio DT9: Construction environmental costs

Table 2. Triangular fuzzy numbers language levels.

Fuzzy Level	Triangular Fuzzy Numbers
Very important (VP)	(3.5, 4.0, 4.5)
Important (P)	(3.0, 3.5, 4.0)
Weakly important (WP)	(2.5, 3.0, 3.5)
Medium important (MP)	(2.0, 2.5, 3.0)
Weak unimportant (WIP)	(1.5, 2.0, 2.5)
Unimportant (IP)	(1.0, 1.5, 2.0)
Very Unimportant (VIP)	(1.0, 1.5, 1.5)
Equally important (EP)	(1.0, 1.0, 1.0)

Step 1: Determine the best and worst customer demand indicators, as well as the green design technical characteristics indicators that have the greatest and least impact on each customer demand, shown in Tables 3 and 4:

Table 3. Best and worst customer demand indicators.

	Best Customer Demand	Worst Customer Demand
Expert 1	CR1	CR3
Expert 2	CR1	CR3
Expert 1	CR1	CR4

Table 4. Indicators of technical characteristics that have the maximum and minimum impact.

Expert 1	Maximum Impact Indicators	Minimum Impact Indicators
CR1	DT6	DT2
CR2	DT5	DT9
CR3	DT7	DT9
CR4	DT9	DT1

Step 2: Determine the best-other vectors and the other-worst vectors of customer demands, as shown in Table 5, for example:

Table 5. Best-other vectors and other-worst vectors.

Expert 1	CR1	CR2	CR3	CR4
Best-other	(1.0, 1.0, 1.0)	(2.0, 2.5, 3.0)	(3.5, 4.0, 4.5)	(1.0, 1.5, 2.0)
Other-worst	(3.5, 4.0, 4.5)	(1.5, 2.0, 2.5)	(1.0, 1.0, 1.0)	(2.5, 3.0, 3.5)

Step 3: Solve for the optimal customer demand indicator assignment as well as the optimal correlation matrix by the triangular fuzzy BWM method, as shown in Table 6.

Table 6. Quality house (Expert 1).

	DT1	DT2	DT3	DT4	DT5	DT6	DT7	DT8	DT9	
CR1	(0.078, 0.078, 0.082)	(0.065, 0.065, 0.077)	(0.153, 0.156, 0.195)	(0.153, 0.156, 0.195)	(0.153, 0.156, 0.195)	(0.183, 0.207, 0.266)	(0.148, 0.193, 0.195)	(0.148, 0.193, 0.195)	(0.077, 0.096, 0.101)	(0.235, 0.353, 0.502)
CR2				(0.153, 0.156, 0.195)	(0.074, 0.416, 0.871)				(0.055, 0.226, 0.328)	(0.180, 0.217, 0.296)
CR3				(0.153, 0.156, 0.195)	(0.178, 0.178, 0.182)	(0.183, 0.183, 0.183)	(0.312, 0.327, 0.419)	(0.312, 0.327, 0.419)	(0.080, 0.080, 0.080)	(0.138, 0.160, 0.174)
CR4	(0.000, 0.082, 0.139)	(0.000, 0.082, 0.139)		(0.153, 0.156, 0.195)	(0.000, 0.136, 0.239)	(0.000, 0.158, 0.308)	(0.000, 0.158, 0.308)	(0.000, 0.158, 0.308)	(0.000, 0.236, 0.528)	(0.180, 0.270, 0.296)
	(0.018, 0.050, 0.082)	(0.015, 0.045, 0.080)	(0.036, 0.053, 0.098)	(0.011, 0.102, 0.230)	(0.038, 0.211, 0.458)	(0.068, 0.145, 0.297)	(0.078, 0.163, 0.262)	(0.062, 0.084, 0.119)	(0.039, 0.159, 0.318)	

Step 4: Transform the customer demand weights into green design technical characteristic index assignments through the QFD quality house and best correlation matrix, as shown in Table 7.

Table 7. Vector of comprehensive best green design technology characterisation indicators.

	DT1	DT2	DT3	DT4	DT5	DT6	DT7	DT8	DT9
Triangular fuzzy weights	(0.078, 0.078, 0.082)	(0.065, 0.065, 0.077)	(0.153, 0.156, 0.195)	(0.153, 0.156, 0.195)	(0.153, 0.156, 0.195)	(0.183, 0.207, 0.266)	(0.148, 0.193, 0.195)	(0.148, 0.193, 0.195)	(0.077, 0.096, 0.101)

Step 5: Integrate and standardise the green design technical features of the three experts to obtain the comprehensive best green design technical feature indicator vector, as shown in Table 7.

Based on the above case study, the relationship between customer demand and green design technology features can be well analysed, and the efficiency of weight solving is greatly accelerated by the BWM.

3.2. Validation of the Triangular Fuzzy TOPSIS–GG Green Design Scheme Evaluation Method

To verify the effectiveness and universality of the proposed triangular fuzzy TOPSIS–GC evaluation method, this section evaluates the three alternative schemes using the hotel green design scheme selection in Section 3.1 above as a case study. Remembering the three schemes as C1, C2, and C3, the following measurements are made by using the multi-expert method and inviting the industry expert group to score the secondary evaluation indicators according to the comprehensive evaluation system of green design developed in Section 3.1:

Step 1: Construct the initial fuzzy decision matrix for hotel green design scheme selection.

To make the evaluation results more reasonable and reduce the evaluation bias, five experts in the industry are invited to reclassify the triangular fuzzy numbers linguistic levels, as shown in Table 8. Evaluation of the alternative schemes is carried out according to the fuzzy linguistic levels. The initial fuzzy decision matrix for the selection of green design schemes for hotels is obtained in accordance with the calculation rules based on the weights of each scheme obtained in Section 3.1, as shown in Table 9.

Table 8. Triangular fuzzy numbers language levels.

Fuzzy Language	Triangular Fuzzy Numbers
Very good (VG)	(9, 10, 10)
Good (G)	(7, 9, 10)
Moderately good (MG)	(5, 7, 9)
Fair (F)	(3, 5, 7)
Moderately poor (MP)	(1, 3, 5)
Very poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)

Table 9. Fuzzy initial decision matrix.

	DT1	DT2	DT3	DT4	DT5
C1	(8.33, 9.66, 10)	(6.33, 8.00, 9.33)	(5.66, 7.66, 9.33)	(5.66, 7.66, 9.33)	(5.00, 7.00, 8.66)
C2	(5.66, 7.33, 8.66)	(6.33, 8.33, 9.66)	(6.33, 8.33, 9.66)	(7.00, 8.66, 9.66)	(7.00, 8.66, 9.66)
C3	(7.00, 8.66, 9.66)	(4.33, 6.33, 8.33)	(7.66, 9.00, 9.66)	(7.00, 8.66, 9.66)	(7.00, 8.66, 9.66)
W	(0.019, 0.049, 0.089)	(0.017, 0.038, 0.087)	(0.018, 0.047, 0.066)	(0.008, 0.120, 0.326)	(0.036, 0.200, 0.449)
	DT6	**DT7**	**DT8**	**DT9**	
C1	(5.66, 7.33, 8.66)	(7.66, 9.00, 9.66)	(5.66, 7.66, 9.33)	(6.33, 8.33, 9.66)	
C2	(7.00, 8.66, 9.66)	(5.66, 7.66, 9.33)	(5.00, 7.00, 8.66)	(7.66, 9.00, 9.66)	
C3	(6.33, 8.00, 9.33)	(7.66, 9.00, 9.66)	(6.33, 8.33, 9.66)	(5.00, 7.00, 8.66)	
W	(0.073, 0.146, 0.282)	(0.057, 0.168, 0.319)	(0.032, 0.074, 0.138)	(0.037, 0.164, 0.37)	

Step 2: Fuzzy normalisation of the fuzzy decision matrix according to the normalisation rules, i.e., Equations (27) and (28), where DT4, DT5, DT6, and DT7 are the positive indicators and the rest are the negative indicators. The fuzzy standardised decision matrix U is obtained, as shown in Table 10.

Table 10. Fuzzy standardised decision matrix.

	DT1	DT2	DT3	DT4	DT5
C1	(0.57, 0.59, 0.68)	(0.46, 0.54, 0.68)	(0.61, 0.74, 1)	(0.59, 0.79, 0.97)	(0.52, 0.72, 0.90)
C2	(0.65, 0.77, 1)	(0.45, 0.52, 0.68)	(0.59, 0.68, 0.89)	(0.72, 0.90, 1)	(0.72, 0.90, 1)
C3	(0.59, 0.65, 0.81)	(0.52, 0.68, 1)	(0.59, 0.63, 0.74)	(0.72, 0.90, 1)	(0.72, 0.90, 1)
W	(0.019, 0.049, 0.089)	(0.017, 0.038, 0.087)	(0.018, 0.047, 0.066)	(0.008, 0.120, 0.326)	(0.036, 0.200, 0.449)
	DT6	**DT7**	**DT8**	**DT9**	
C1	(0.59, 0.76, 0.90)	(0.79, 0.93, 1)	(0.54, 0.65, 0.88)	(0.52, 0.60, 0.79)	
C2	(0.72, 0.90, 1)	(0.59, 0.79, 0.97)	(0.58, 0.71, 1)	(0.52, 0.56, 0.65)	
C3	(0.66, 0.83, 0.97)	(0.79, 0.93, 1)	(0.52, 0.60, 0.79)	(0.58, 0.71, 1)	
W	(0.073, 0.146, 0.282)	(0.057, 0.168, 0.319)	(0.032, 0.074, 0.138)	(0.037, 0.164, 0.37)	

Step 3: Calculate the fuzzy weighted normalised decision matrix F according to Equation (30), as shown in Table 11.

Table 11. Fuzzy weighted standardised decision matrix.

	DT1	DT2	DT3	DT4	DT5
C1	(0.01, 0.03, 0.06)	(0.01, 0.02, 0.06)	(0.01, 0.03, 0.07)	(0.00, 0.09, 0.31)	(0.02, 0.14, 0.40)
C2	(0.01, 0.04, 0.09)	(0.01, 0.02, 0.06)	(0.01, 0.03, 0.06)	(0.01, 0.11, 0.33)	(0.03, 0.18, 0.45)
C3	(0.01, 0.03, 0.07)	(0.01, 0.03, 0.09)	(0.01, 0.03, 0.05)	(0.01, 0.11, 0.33)	(0.03, 0.18, 0.45)
	DT6	**DT7**	**DT8**	**DT9**	
C1	(0.04, 0.11, 0.25)	(0.05, 0.16, 0.32)	(0.02, 0.05, 0.12)	0.02, 0.10, 0.29)	
C2	(0.05, 0.13, 0.28)	(0.03, 0.13, 0.32)	(0.02, 0.05, 0.14)	0.02, 0.09, 0.24)	
C3	(0.05, 0.12, 0.27)	(0.05, 0.16, 0.32)	(0.02, 0.04, 0.11)	0.02, 0.12, 0.37)	

Step 4: The fuzzy positive ideal schemes F^+ and fuzzy negative ideal schemes F^- are determined according to Equations (31) and (32).

$$F^+ = [(0.01, 0.04, 0.09)(0.01, 0.03, 0.09)(0.01, 0.03, 0.07)(0.01, 0.11, 0.33)$$
$$(0.03, 0.18, 0.45)(0.05, 0.13, 0.28)(0.05, 0.16, 0.32)(0.02, 0.05, 0.14)(0.02, 0.12, 0.37)]$$

$$F^- = [(0.01, 0.03, 0.06)(0.01, 0.02, 0.06)(0.01, 0.03, 0.05)(0.00, 0.09, 0.31)$$
$$(0.02, 0.14, 0.40)(0.04, 0.11, 0.25)(0.03, 0.13, 0.31)(0.02, 0.04, 0.11)(0.02, 0.09, 0.24)]$$

Step 5: Euclidean distance is calculated between each alternative scheme and the fuzzy positive and negative ideal schemes according to Equations (33) and (34); e.g., alternative 1 is calculated as follows.

$$D_1^+ = \sqrt{\tfrac{1}{3}\left((0.01-0.01)^2+(0.03-0.04)^2+(0.06-0.09)^2\right)} + \sqrt{\tfrac{1}{3}\left((0.01-0.01)^2+(0.02-0.02)^2+(0.06-0.09)^2\right)} + \cdots\cdots + \sqrt{\tfrac{1}{3}\left((0.02-0.02)^2+(0.10-0.12)^2+(0.29-0.37)^2\right)} = 0.165$$

$$D_1^- = \sqrt{\tfrac{1}{3}\left((0.01-0.01)^2+(0.03-0.03)^2+(0.06-0.06)^2\right)} + \sqrt{\tfrac{1}{3}\left((0.01-0.01)^2+(0.02-0.02)^2+(0.06-0.06)^2\right)} + \cdots\cdots + \sqrt{\tfrac{1}{3}\left((0.02-0.02)^2+(0.10-0.09)^2+(0.29-0.24)^2\right)} = 0.061$$

The positive and negative ideal distance calculations for each scheme are shown in Table 12.

Table 12. Positive and negative ideal distances for each scheme.

Schemes	Positive Ideal Distance	Negative Ideal Distance
C1	0.165	0.061
C2	0.116	0.112
C3	0.042	0.185

Step 6: The fuzzy relative closeness of each alternative scheme to the fuzzy positive ideal schemes is calculated. For example, the fuzzy relative closeness of scheme 2 is calculated as follows.

$$G_2 = \frac{0.112}{0.116 + 0.112} = 0.491$$

The final fuzzy relative closeness of each alternative scheme is calculated as G_1 = 0.266, G_2 = 0.491, and G_3 = 0.815.

Step 7: Calculate the fuzzy GC method distance matrix B according to Equation (36) shown in Table 13.

Table 13. Distance matrix of fuzzy GC methods.

	DT1	DT2	DT3	DT4	DT5
C1	0.017	0.017	0	0.014	0.037
C2	0	0.017	0	0	0
C3	0.013	0	0.011	0	0
	DT6	**DT7**	**DT8**	**DT9**	
C1	0.022	0	0.01	0.048	
C2	0	0.022	0	0.077	
C3	0	0	0.018	0	

Step 8: Calculate the fuzzy grey relational coefficient matrix R^+ according to Equation (37) shown in Table 14.

Table 14. Matrix of fuzzy grey relational coefficients.

	DT1	DT2	DT3	DT4	DT5
C1	0.958	0.958	1	0.965	0.912
C2	1	0.958	1	1	1
C3	0.967	1	0.972	1	1
	DT6	**DT7**	**DT8**	**DT9**	
C1	0.946	1	0.975	0.889	
C2	1	0.946	1	0.833	
C3	1	1	0.955	1	

Step 9: The fuzzy grey relational coefficients between each alternative scheme and the fuzzy positive ideal schemes are calculated. For example, the fuzzy grey relational coefficients between scheme 1 and the fuzzy positive ideal schemes are calculated as follows.

$$R_i^+ = \frac{0.958 + 0.958 + 1 + 0.965 + \cdots\cdots + 0.889}{7} = 0.956$$

The final fuzzy grey relational coefficients for each scheme are calculated as $R_1^+ = 0.956$, $R_2^+ = 0.971$, and $R_3^+ = 0.988$.

Step 10: Calculate the composite closeness index ZS_i according to Equation (40).

The final calculations are $ZS_1 = 0.611$, $ZS_2 = 0.731$, and $ZS_3 = 0.902$; i.e., scheme 3 is the most effective in the green design process of the hotel.

To validate the effectiveness of the triangular fuzzy TOPSIS–GC, in this section, DANP [59] and two classical MCDM methods VIKOR [60] and COPRAS [61] are chosen to evaluate the above hotel green design schemes and the evaluations obtained by triangular fuzzy TOPSIS–GC are used to compare the results. COPRAS belongs to the multiattribute decision-making analysis method that allows for combining the importance and utility of evaluation metrics when evaluating solutions. VIKOR has the advantage of being able to synthesise all conflict indicators. DANP can effectively identify the causal relationships that exist within each of the relevant factors and evaluate each scheme through a comprehensive consideration of the relevant factors. These three methods have been widely used by researchers and proved to be superior, and comparison with them can effectively determine the validity of the triangular fuzzy TOPSIS–GC. For ease of observation, the evaluation results of these four methods are presented in a line graph in Figure 4.

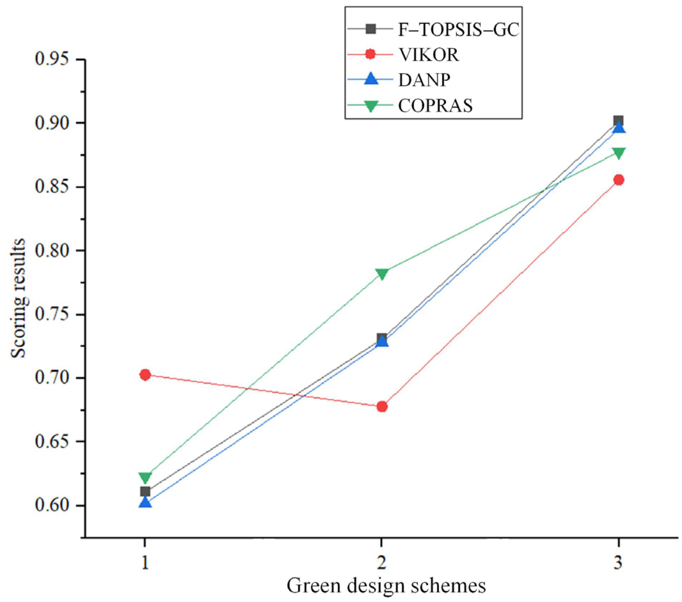

Figure 4. Comparison results of four MCDM approaches.

According to the results in Figure 4, among the three green design schemes for hotels, scheme 3 scores the highest, which can best meet the green design requirements and user needs for hotels, and its evaluation values of the nine indicators are dominant. Scheme 1 ranked the lowest of the three algorithmic evaluations because the raw evaluation values for most of the indicators in scheme 1 are worse than those of the other schemes. As shown in Figure 4, the trends in the evaluation results of these three methods for the schemes are also consistent. This shows that the triangular fuzzy TOPSIS–GC method resides in good applicability. However, there is also some variability in the results of the four methods of evaluation. For example, scheme 1 ranked second among the VIKOR methods but second among three other methods. After analysis, the factors contributing to this evaluation results are as follows: (1) The evaluation principles in VIKOR differ from the other three methods. VIKOR emphasises the eclectic nature of the decision-making scheme, which meets the needs of all parties as much as possible. (2) Various methods differ in the degree of utilisation of information, and some information is lost in the process of refining the collection of dispersed information.

4. Conclusions

With the continuous promotion of the world's resource conservation, circular economy, and other policies, as well as the increasing consumer demand for building personalisation, how to carry out building design scientifically has become a topical area for research. The evaluation of building green performance and optimisation of resource allocation based on customer satisfaction is significant for enhancing the quality and efficiency of building design, enhancing the degree of the greening of building design, improving the degree of response to customer demand, and responding to the global call for low carbon. The research reported here takes customer satisfaction as the guide in the process of building innovation and design, with green performance evaluation and the reasonable and effective allocation of resources as the goal. This paper used hotels as the research object to investigate building green performance evaluation and resource allocation optimisation based on customer satisfaction. The final realisation of the building innovation and design phase of research and development and resource allocation provides theoretical guidance so that the building design takes into account the enterprise's own resources, consumer demand, and the requirements of the green performance of the building. The research is summarised below:

(1) Proposing a method for solving the weights of green design indexes considering customer demand and correlation analysis of green design. To better characterise the uncertainty and randomness of the green design process, triangular fuzzy numbers are employed. The QFD methodology is adopted to establish a quality house to explore fully the correlation between customer needs and green design indicators. QFD and BWM are combined to solve the green design weighting problem with known index weights. The hotel example demonstrates that the proposed triangular fuzzy QFD–BWM fusion method is convenient in the evaluation of green building design index weights.
(2) Developing a method for evaluating green building design schemes in fuzzy situations. To deal with uncertainties in the evaluation process and satisfy the accuracy of the evaluation, a hybrid triangular fuzzy TOPSIS–GC method is proposed to make a reasonable scheme choice using the hotel green design as an example. The evaluation results are compared with the COPRAS, VIKOR, and DANP methods, and the comparison results show that the proposed triangular fuzzy TOPSIS–GC fusion method has good results in evaluating and selecting green building design schemes. This research provides a new basis for addressing the evaluation of green building design schemes and further improves the ability to select and evaluate green building design schemes.

This research also has some limitations. At present, the building green design index weight evaluation method and green design scheme evaluation method proposed in this paper only integrate triangular fuzzy numbers. In the future, regarding the building green design evaluation, we can consider improving the fuzzy characterisation, and we can also consider combining different fuzzy characterisations. The current algorithm still has room for improvement, and subsequent research can enhance the convergence ability and solving efficiency of the algorithm to obtain better green building design schemes by setting an adaptive selection strategy for the optimisation rules, setting an enhanced local search operator, and integrating Q-learning strategies.

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