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Case-based reasoning approach for supporting building green retrofit decisions

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ABSTRACT

Building green retrofit is considered as an effective means of energy saving and achieving sustainable development goals. The success of a building retrofit is highly dependent on the retrofit strategies used. However, it remains challenging to select appropriate retrofit strategies for a specific retrofit building. There are numerous cases of building retrofit around the world, which can be collected, stored, and analysed. The knowledge gained from these cases could provide a useful reference for making decisions on new retrofitting projects. This study presents a case-based reasoning (CBR) approach to support building green retrofit decisions. A total of 71 retrofit cases in China were collected. The attributes of the retrofitting buildings were identified, including the general building information, component information, and energy and cost information. A synthetic optimisation weighting method was adopted based on both expert opinion and the attribute characteristics. A real retrofit case located in Shanghai was used as a case study to demonstrate the application of the CBR approach. The results indicate that the CBR approach can aid in identifying similar cases from the case database, and extracting valuable information from these. The experience and lessons learned from past cases can guide decision makers in making improved decisions on new green retrofit projects.

1. Introduction

Buildings are major consumers of energy, particularly during the operation stage, contributing to a large proportion of the total energy use globally [1,2]. In China, the building sector accounts for approximately 27.45% of the total energy consumption. In 2017, China's existing building area exceeded 56 billion square meters, and over 97% of the existing buildings are highly energy consuming [3,4]. Therefore, in addition to designing new green buildings, the rapid enhancement of energy efficiency in existing buildings is essential for substantially reducing the adverse impacts of buildings on the environment. This topic has attracted significant attention from both the government and public. In China, the "Assessment Standard for Green Retrofitting of Existing Building" was placed into effect in 2016 to promote green retrofitting of existing buildings. According to the World Green Building Trends 2016 Report, 37% of global respondents expected to undertake green retrofit projects in the following three years [5]. Thus, green retrofitting of existing buildings is now a major trend around the world, which is expected to achieve significant energy savings in the building sector.

It is widely acknowledged that the success of building retrofitting is highly dependent on the retrofit strategies adopted [6,7]. Retrofit strategies range from the use of energy-efficiency equipment, advanced controls, and renewable energy systems to advanced heating and cooling technologies [1]. By implementing appropriate retrofit strategies, the building energy performance can be significantly improved, and the total cost should be within the owner budget [8]. Thus, it is important to make proper decisions in building green retrofitting, which are both energy efficient and cost effective. Numerous research efforts have been devoted to providing decision support for selecting optimal retrofit strategies [6,9,10]. Multi-criteria decision-making methods have been used extensively [6,9,11,12]. Furthermore, economic analysis tools and other risk assessment tools have been used to compare different retrofit alternatives and select the most preferable option [13]. All this research has laid a solid foundation for the decision-making process of green retrofitting. However, the majority of

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previous studies used mathematical models based on various assumptions. The assumptions used in quantitative models may not reflect real situations in practice. In fact, the decision-making of green retrofitting is a complex process involving numerous factors.

With the increase in green retrofit projects globally, the experiences gained from completed retrofit projects could provide a valuable reference for supporting new building retrofit decisions [14,15]. However, in contrast to new buildings, existing buildings have already been built, and their current conditions differ. For example, the age, energy consumption, and structure of buildings vary. These features influence decision-making when selecting green retrofit strategies. Therefore, green retrofit experience gained previously in similar buildings can provide a useful reference for new retrofit projects with similar features. Thus, it appears necessary to develop a matching method to select the most similar green retrofit cases for a target building that will be retrofitted. Case-based reasoning (CBR) is regarded as a useful approach for retrieving similar cases from an established case database to aid in solving problems encountered in new cases [16]. The approach has already been applied in various fields [17,18]. Researchers have suggested that CBR is suitable for unstructured and complex problems [19,20]. As green retrofit decision-making is a complicated process, CBR is therefore considered as effective for supporting green retrofit decisions. However, few studies have been conducted on supporting the decision-making of green retrofit strategies by learning from similar past projects.

Therefore, this study presents a CBR approach to support building green retrofit decisions. The remainder of this paper consists of the following sections. The related literature is reviewed in Section 2. The CBR method and analytic hierarchy process (AHP)–entropy method are introduced in Section 3. In Section 4, the CBR system is developed for an existing building, the building attributes are identified, and the similarity measurement between retrofit cases is introduced. In Section 5, the implementation of the proposed CBR approach in a real case is presented to validate the proposed methodology. Finally, Section 6 presents the conclusions of this study.

2. Literature review

Green retrofitting refers to making alterations to existing buildings, including the architectural design, componentry, and operations [21], with the aim of making existing buildings more environmentally friendly, which offers significant opportunities for reducing energy consumption and greenhouse gas emissions [1,6]. Many studies have been conducted on building green retrofitting, including building performance assessment [22–25], selection of retrofit strategies [6,7,26], retrofit economic analysis [8,27,28], and retrofit risk assessment [1,29,30].

The selection of retrofit strategies is important for a retrofit project. Therefore, numerous research efforts have been devoted to developing various decision-making tools to aid in making improved decisions on retrofit strategies. Multiple criteria, such as economic, environmental, and social criteria, are commonly used in these tools [11]. Multi-objective optimisation models have been applied with the aim of achieving these goals. For example, Juan et al. [10] developed an integrated decision support model for the sustainable renovation of existing office buildings by considering the renovation cost, improved building quality, and environmental impacts. Jafari and Valentin [9] presented a multi-objective model to select the optimal energy retrofitting strategy by considering the potential investors and potential benefits. The results demonstrated that stakeholders may make different selections of objective functions, which may affect the final decisions on building retrofits. In addition to multi-objective methods, several researchers have used economic analysis methods to solve building retrofit problems. The net present value method has been used extensively to analyse the financial feasibility of retrofit plans [8,27,28]. In this approach, decisions are made based on the economic performance of all retrofit plans, which are derived from an economic analysis model. Moreover, the option pricing theory has been used to evaluate the economic performance of retrofit options [13]. In most of these studies, mathematical models were developed to solve decision problems for a specific building. These methods are considered as effective according to the conditions set in the research. However, real retrofit cases are more complicated, and vary from one to another. When certain conditions change, the solutions derived from the mathematical model may not be effective. Thus, when resolving certain decision problems for green retrofitting, establishing a certain decision model may not be as effective as directly referring to past experience, particularly for similar and successful cases. Based on this consideration, it is necessary to establish rapid and accurate matching to similar past retrofit cases. The CBR method is considered as appropriate for this purpose, and can make the decision-making process more efficient.

The CBR method refers to the process of solving new problems based on the solutions of similar past problems [16,31]. The method has been applied successfully in various fields, such as medical diagnoses [32], legal cases [33], engineering design [34], and risk assessment and prediction [35]. Because CBR conforms to the building designer cognitive process, it has also been successfully applied in architectural design and construction management. For example, Koo and Hong [36] used CBR to evaluate the historical trends of the energy performance of existing buildings. Cheng and Ma [31] introduced a CBR approach to aid in setting target credits in Leadership in Energy and Environmental Design (LEED) projects. Shen et al. [19] adopted CBR to support green building design. CBR provides an effective means of identifying similar cases and retrieving previous successful experience, which provide a useful reference for building designers in solving various unstructured and complex problems during the design process. However, few studies have been conducted on the implementation of CBR in building retrofitting.

Thus, based on the above review, this study aims to develop a CBR approach to support existing building retrofit decisions. Based on a database containing numerous past green retrofit cases, the CBR approach can match and retrieve useful information from previous cases, which can be used as references for new retrofit projects. Furthermore, past successful experiences are meaningful for new green retrofit projects, and therefore, the problems of using mathematical models can be avoided.

3. Research methodology

3.1. CBR

CBR is used to solve a new problem by extracting useful solutions adopted previously in solving certain types of problems [37]. CBR is essentially in line with the human cognitive process. When people encounter new problems and situations, they generally use their experiences of past similar problems to solve the new problem. The new problem is referred to as the target case, and the past cases are stored in a case database [38]. Relevant experience can be retrieved from the database following matching by using CBR. A CBR system usually contains four components: a case database for storing past cases and their corresponding solutions, attributes of cases for representing cases, similarity measurement methods for matching cases, and a modification method for case adjustment [20]. The CBR process can be regarded as a circle composed of five parts: represent, retrieve, reuse, revise, and retain [39]. Firstly, a new problem encountered is "represented" as a target case. Then, similar cases will be "retrieved" from the case database. The solution to these similar past cases will be "reused" for the new case. The suggested solution may be "revised" to adapt to the new conditions. Thereafter, a new case and its corresponding solution are generated, which will be "retained" in the case database.

The case retrieval performance is the core component of the CBR approach [16]. The most commonly used method for measuring the similarity of two cases is the local–global similarity [31], which is a two-step approach. The local similarity, which refers to the similarity among each case attribute, is calculated first. After weights are assigned to each attribute, the global similarity is obtained by integrating the derived local similarity. Thus, the weights play an important role in determining the final global similarity. To improve the weighting accuracy, the AHP–entropy weighting method is used in this study, which considers both the stakeholder opinions of the target building and data from past retrofit cases.

3.2. AHP–entropy

The AHP, developed by Thomas L. Saaty [40], is a structured technique for organising and analysing complex decisions based on the hierarchy analysis process. It provides a comprehensive and rational framework for structuring a decision problem. Once the hierarchy has been constructed, the decision makers systematically evaluate its various elements by comparing them to one another two at a time, with respect to their impact on an element above them in the hierarchy [41]. As a numerical weight or priority is derived for each element of the hierarchy, the AHP can be used to determine the weighting coefficients of the indices in the evaluation system. This is all based on subjective evaluation of the decision makers, and thus, this approach is referred to as the subjective weighting method in this study.

Entropy originates from information theory, and refers to the degree of system confusion [42]. In the entropy weighting method, the weights are determined by measuring the entropy of each index. The entropy weighting method can be explained as follows: a smaller entropy of the index results in a smaller amount of information that the index can provide, and a smaller effect of the index in the comprehensive evaluation system, thereby resulting in a lower weight. Because the numerical weighting values are derived from the entropy of the objective data, which does not change with the decision makers [43], the entropy weighting method is referred to as the objective weighting method in this study.

The AHP–entropy method refers to a synthetic weighting approach that integrates both the AHP and entropy weighting methods [42]. In terms of AHP weighting methods (subjective weighting methods), which are completely dependent on the opinions of the domain decision makers, the weight results may vary when different decision makers are invited to make varying decisions [40]. Therefore, it is not reasonable to determine weights depending only on decision maker opinions. However, regarding entropy weighting methods (objective weighting methods), the high dependence on the data among each attribute, without considering opinions, may result in the derived weights not making sense at times [43]. Thus, both weighting methods exhibit limitations when applied in practice. Moreover, during the green retrofit case retrieval process, the stakeholder opinions and data features in the past cases are both important when assigning weights to the indices of retrofit buildings [9]. Therefore, by combining both the subjective and objective weighting methods, AHP–entropy can fully emphasise the role of each part in determining the final weights, and overcome all of these shortcomings. The mechanism of the AHP–entropy method is that both subjective and objective weights are obtained during the first step, and then, by means of a mathematical programming model, the final weights can be obtained based on the above two parts of weights [42].

4. Framework of CBR approach for green retrofit decisions

When using CBR for existing building retrofit projects, the five phases of CBR can be described as follows:

(1) Represent: Determining the manner in which the retrofit case is presented in the database. In this part, key attributes of retrofit buildings are used to represent retrofit cases. Retrofit strategies are not included, but are attached to each case, because they do not influence the similarity between the target case and the cases in the database. The collected cases are represented using the same attributes, and stored in the case database. The target retrofit case is represented by the same attributes to match the cases in the database.
(2) Retrieve: For a target building retrofit case, cases with high similarity are retrieved from the case database. In this part, the key issue is to determine the similarity between two cases. Thus, the local similarity between each attribute is calculated first. Thereafter, the global similarity is determined by integrating the local similarities with weightings. The cases with high global similarities are retrieved for further analysis.
(3) Reuse: The detailed information of the cases with high global similarities can be retrieved from the database, including the retrofit strategies adopted in these cases. These retrofit strategies are considered for "reuse" or "reuse after adaptation" in the target building, and provide a useful decision reference for the new retrofit project.
(4) Revise: If the retrofit solutions adopted in the retrieved retrofit cases cannot fully satisfy the stakeholder demands, certain adjustments are required to make the solutions viable and meet stakeholder expectations.
(5) Retain: After successful implementation of the target retrofit project, all of the information is represented in the format specified in step (1), and stored in the retrofit case database for future use.

The framework of the CBR approach for building green retrofitting is illustrated in Fig. 1. Because the "retain" phase is easy to understand and carry out in practice, it will not be explained further. The other four steps in the CBR approach are clearly introduced in the following sections.

4.1. Case representation

Case representation involves defining the attributes and structure for describing a case [44]. These attributes can be used to represent the building retrofit features. As discussed in previous studies, the general building information (such as the building type and gross area) [45], detailed assessment information regarding the building condition before retrofitting [46], energy consumption change information, and cost information [27] are important for representing a building retrofit case.

Regarding the general building information, various attributes have been used to describe a building. For example, Cheng and Ma [31] used six attributes, namely the project type, owner type, gross square feet, total property area, grade level, and location. These six attributes were selected because they are also used by the U.S. Green Building Council (USGBC), from which their values can be obtained. Shen et al. [19] identified six major attributes for describing a green building case, namely the gross square feet, project type, owner type, climate zone, level of green grade, and cost. Kuo et al. [47] selected attributes including the year of application, distribution area, total floor area, and building type to describe a building. Volk et al. [48] noted that the building information, such as the age (new, existing or heritage), types of use (such as residential, commercial, municipal or infrastructural), ownership (including private owner, housing association, authorities or universities) varied and all have an influence on the building maintenance and retrofitting. Therefore, based on the above previous studies and data availability of existing buildings, five attributes were selected for representing the general building information, namely the built year (building age), building type, ownership type, building size, and building location.

In addition to the general building information, more specific building performance information, known as component information, is necessary for describing a retrofit case, which includes the building envelope, Heating, Ventilating and Air Conditioning (HVAC) system,

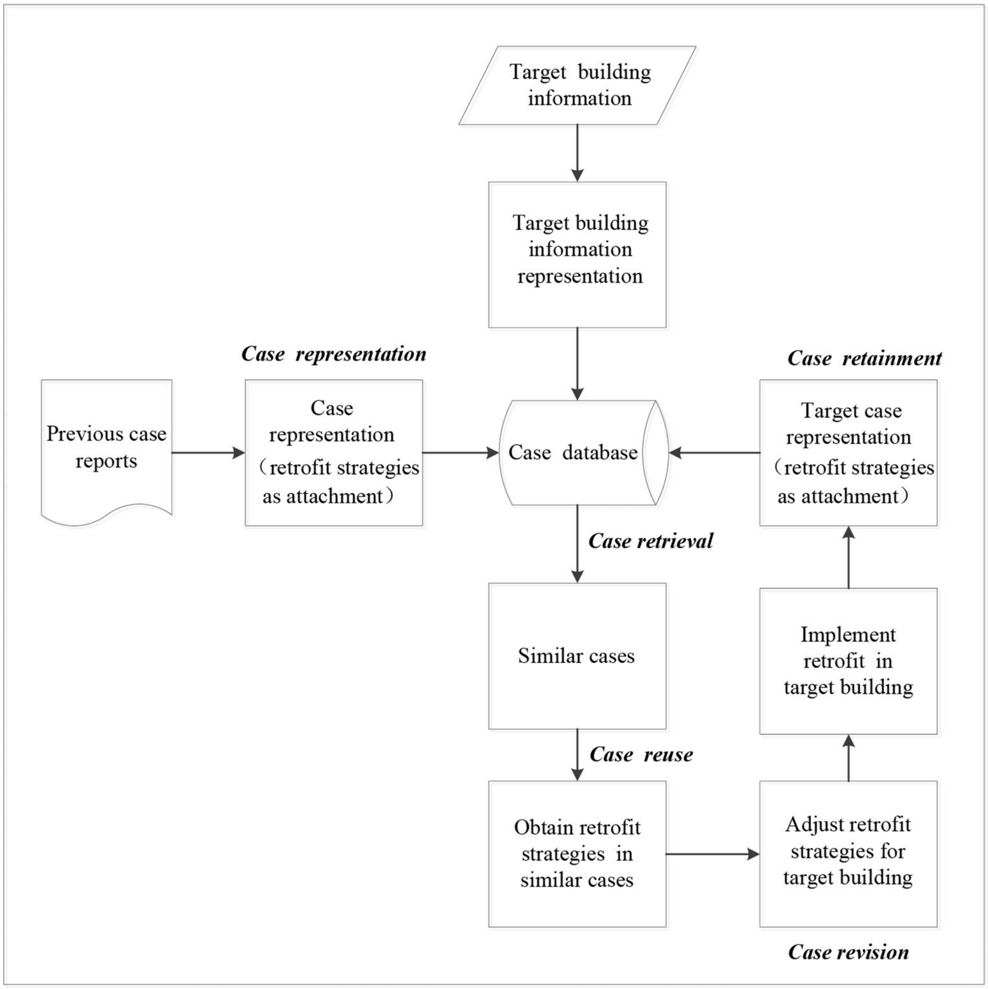

Fig. 1. Framework of proposed CBR approach for building green retrofit.

lighting, and water system. The detailed component information fully describes the condition of each building component prior to retrofitting, which aids in evaluating the similarity between retrofit cases. For example, if two cases are found to exhibit poor building envelope conditions, the retrofit strategies of one case can provide a strong reference for the other case. A building envelope separates its interior from the external environment, and includes roofs, walls, windows, and doors. The envelope is crucial in determining the building energy efficiency according to its insulation function, because the building envelope determines the heat loss or gain in a building. When the insulation level of the building envelope is poor, the energy consumption for heating or cooling will be high. Apart from the building envelope, the HVAC and electric lighting systems both require a large amount of energy in a building. HVAC accounts for almost 50% of the building energy consumption, while the lighting system consumes approximately 25% of the energy [49]. These components directly influence the building energy performance. Moreover, water consumption is an important component, which reflects the water-efficient level of a building. Fuzzy terms (extremely low, low, medium, high, and extremely high) are used for the component information, because quantitative data are not available for all cases.

Energy information and financial information are two core parts of a building retrofit case, which are also major stakeholder concerns. Many building owners implement green retrofitting mainly because the current energy consumption is high, and thus, the annual energy cost is high. Therefore, the energy consumption and financial burden are major concerns for building owners, and play an important role in determining which retrofit strategies should be adopted [1,6,27,50]. Therefore, the energy consumption, retrofit budget, and payback period were selected in this study to represent the energy and cost information.

Thus, all of the attributes for representing building retrofit cases were selected, and are displayed in Table 1. The cost information and payback period information refer to the expected retrofitting performance of the target retrofitting case for the owner. The fuzzy terms were obtained by the evaluation by experts from professional design institutes, based on the Design Standard for Energy Efficiency of Buildings issued by the Ministry of Housing and Urban-Rural Development (MOHURD) of the People's Republic of China, as all the cases were collected in China.

4.2. Case retrieval

Case retrieval is the process of identifying the most similar cases from the case database, according to the similarity measurement [38]. In this section, the local–global method is used as the similarity measurement method. The local–global method includes two steps [31]: the first is calculating the local similarities between different cases for each attribute; the second is to calculating global similarity by aggregating the local similarities of the attributes. It is necessary to determine the weightings of attributes when aggregating the local similarities. In this study, the AHP–entropy method was used to determine the attribute weightings.

Table 1
Attributes for retrofit cases and corresponding descriptions.

First-level attributes	Second-level attributes	Description
A: General information	A1: Built year	Year
	A2: Building type	Office, commercial, residential, retail, public assembly, others
	A3: Ownership type	Government, for-profit corporation, non-profit corporation
	A4: Building size	Gross floor area (m^2)
	A5: Climate zone	China's building climate zoning map
B: Component information (before retrofitting)	B1: Insulation level of building envelope	Fuzzy terms
	B2: Energy-efficient level of HVAC system	Fuzzy terms
	B3: Energy-efficient level of lighting system	Fuzzy terms
	B4: Water-efficient level of water installations	Fuzzy terms
C: Energy and cost information	C1: Annual electricity consumption per m^2 before retrofitting	kWh/m^2
	C2: Estimated retrofit budget	RMB
	C3: Estimated payback period	Years

4.2.1. Local similarity measurement

The local similarity refers to the similarity of the attributes between the target case and the cases in the database. For the attributes identified in section 4.1, the local similarity measurement is introduced as follows.

1 Categorical attributes

Categorical attributes refer to the building type, ownership type, and climate zone. For the categorical attributes, the similarity between retrofit cases can be measured by determining whether or not they have the same value using Eq. (1) [51].

$$ls^j_{(c_0,c_i)} = \begin{cases} 1 \ if \ v^j_0 = v^j_i \\ 0 \ if \ v^j_0 \neq v^j_i \end{cases}, \tag{1}$$

where c_0 represents the target case and c_i represents the ith previous case in the case database. Moreover, $ls^j_{(c_0,c_i)}$ denotes the local similarity of attribute j between cases c_0 and c_i, v^j_i denotes the value of attribute j with regard to case i, and v^j_0 denotes the value of attribute j with regard to the target case.

2 Crisp numeric attributes

For crisp numeric attributes, such as the built year, building size, annual energy consumption before retrofitting, estimated retrofit cost, and estimated payback period, the similarity can be measured according to the distance between the target case and cases in the database. A shorter distance implies greater similarity. The distance between the crisp numeric attributes can be calculated by Eq. (2) [52].

$$ls^j_{(c_0,c_i)} = 1 - |v^j_i - v^j_0|/(\overline{v^j_i} - \underline{v^j_i}). \tag{2}$$

In the above, the meanings of $ls^j_{(c_0,c_i)}$, c_0, c_i v^j_i, and $v^j_0$are the same as those in Eq. (1), where $\overline{v^j_i}$ is the maximum value of attribute j in the case database, and $\underline{v^j_i}$ is the minimum value.

3 Fuzzy linguistic attributes

In building retrofitting, the fuzzy linguistic attributes include the insulation level of the building envelope, energy-efficient level of the HVAC system, energy-efficient level of the lighting system, and water-efficient level of the water installations. The trapezoidal membership function [53] is used to describe the fuzzy linguistic attributes. The score intervals of the fuzzy linguistic terms are presented in Table 2, and the corresponding membership functions are illustrated in Fig. 2. The similarity between two fuzzy linguistic terms can be calculated according to Eq. (3) [53].

Table 2
Score intervals of fuzzy linguistic terms.

Fuzzy term	Score intervals
Extremely low	0–19
Low	20–39
Medium	40–59
High	60–79
Extremely high	80–100

$$ls^j_{(c_0,c_i)} = 1 - \frac{\int_\alpha^\beta \int_\alpha^\beta \mu(x)\mu'(y)|x-y|dxdy}{(\beta-\alpha)\int_\alpha^\beta \mu(x)dx \int_\alpha^\beta \mu'(y)dy}, \tag{3}$$

in which the meanings of $ls^j_{(c_0,c_i)}$ are the same as those in Eq. (1). Here, α and β represent the boundaries of the membership functions, while $\mu(x)$ and $\mu'(y)$ denote the membership functions.

4.2.2. Attribute weightings

The AHP–entropy method was adopted to determine the attribute weightings. The AHP method is used to obtain subjective weightings by conducting pairwise comparisons. Let $D(D = \{d_1, d_2, ..., d_t\})$ represent the set of decision makers and $z(z = (z_1, z_2, ..., z_t)^T)$ represent the weight of each decision maker. This study assumes an equal weight for each decision maker; that is, $z_k = 1/t$. There are n attributes in total, and $A_k(A_k = (a^k_{ij})_{n\times n})$ represents the decision matrix of each decision maker. A consistency test was conducted to evaluate whether the matrix was reasonable and reliable. The consistency index $C.\ I.$ and consistency ratio $C.\ R.$ can be obtained from Eqs. (4) and (5), respectively, with λ_{max} being the maximum eigenvalue and $R.\ I.$ being the random index. If $C.\ R.\ < 0.1$, the judgement matrix is consistent. Once all of the matrices have passed the consistency test, the final group decision matrix integrating all of the decision maker judgments, denoted by $A(A = (a_{ij})_{n\times n})$, can be obtained. Then, the subjective weights can be obtained by calculating the eigenvectors of A.

$$C.\ I. = \frac{\lambda_{max} - n}{n-1} \tag{4}$$

$$C.\ R. = \frac{C.\ I.}{R.\ I.} \tag{5}$$

The entropy method was used to obtain the objective weightings. The local similarities derived from the comparison with each past case can be viewed as the standardised data among the attributes. It is assumed that there were m retrofit cases in the case database, and n attributes. All of the local similarities form a matrix denoted by $LS(LS = (ls^j_{(c_0,c_i)})_{m\times n})$ with $i = 1,2, \cdots, m$ and $j = 1,2, \cdots, n$. Let E_j denote the entropy of attribute j. Then, the objective weights can be calculated according to Eqs. (6)–(8). In particular, if $p_{ij} = 0$, let $p_{ij}lnp_{ij} = 0$.

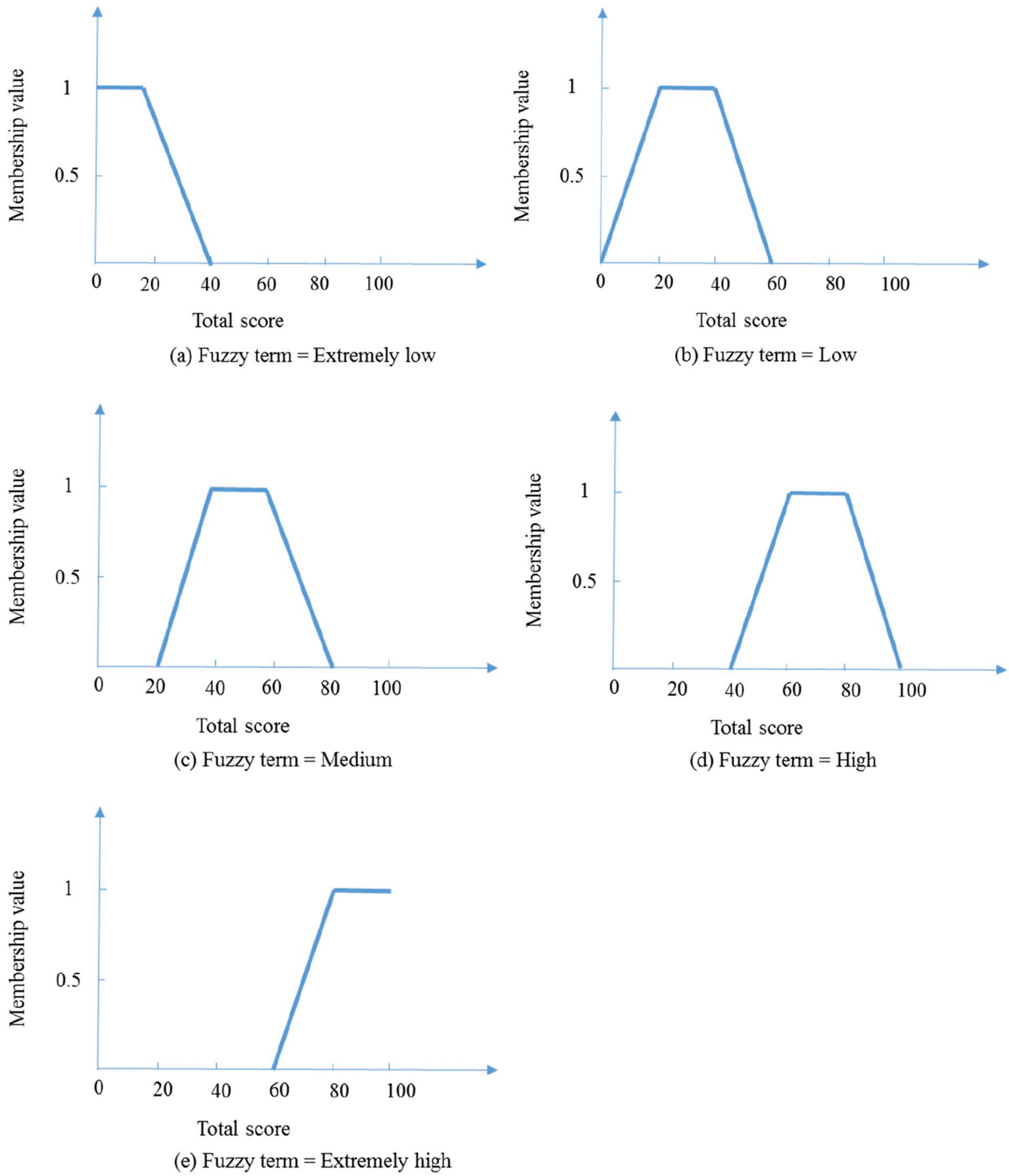

Fig. 2. Fuzzy membership functions of fuzzy linguistic terms.

$$p_{ij} = \frac{ls^{j}_{(c_0,c_i)}}{\sum_i^m ls^{j}_{(c_0,c_i)}} \tag{6}$$

$$\mathrm{E}_j = -(lnm)^{-1} \sum_{i=1}^{m} p_{ij} lnp_{ij} \tag{7}$$

$$W_j = \frac{1 - E_j}{n - \sum_{j=1}^{n} E_j} \tag{8}$$

Let the subjective weights referring to the expert opinions be w^s, where $w^s = (w_1^s, w_2^s, \cdots, w_n^s)$, which satisfy $0 \le w_j^s \le 1$ and $\sum_{j=1}^{n} w_j^s = 1$. Similarly, let the objective weights derived from the data be w^o, where $w^o = (w_1^o, w_2^o, \cdots, w_n^o)$, also satisfying $0 \le w_j^o \le 1$ and $\sum_{j=1}^{n} w_j^o = 1$. Then, the final weight vector can be represented as w, where $w = \alpha w^s + \beta w^o$, $\alpha, \beta \ge 0,\ \alpha + \beta = 1$.

The subjective and objective weights both represent the weights of attributes. If the two weights are consistent with one another, both weight vectors can be regarded as credible, and the combined weights are also credible. Based on this consideration, a model aimed at reaching the highest consistency between the subjective and objective weights was constructed to obtain the coefficients α and β. It is already known the weighted local similarity can be expressed as $ls^{j}_{(c_0,c_i)}\ w_j$. Thus, the degree of deviation between the subjective and objective weights with regard to case i can be expressed as

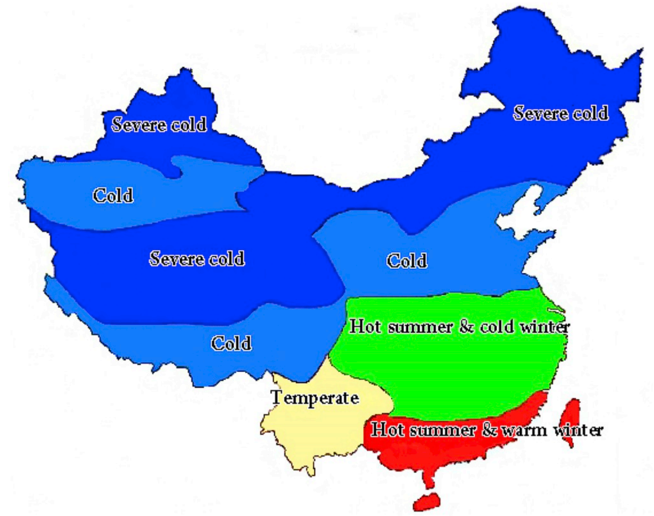

Fig. 3. China's building climate zone map (issued by MOHURD).

$d_i = \sum_{j=1}^{n} (\alpha ls_{(c_0,c_i)}^{j} w_j^s - \beta ls_{(c_0,c_i)}^{j} w_j^o)^2$, $i = 1,2, \cdots, m$. Then, the entire optimisation model is expressed as follows:

$$\text{MinZ}= \sum_{i=1}^{m} d_i = \sum_{i=1}^{m} \sum_{j=1}^{n} \left(\alpha ls_{(c_0,c_i)}^{j} w_j^s - \beta ls_{(c_0,c_i)}^{j} w_j^o \right)^2 \tag{9}$$

s.t. $\alpha + \beta = 1$, $\alpha, \beta \geq 0$.

The model solution is as follows:

$$\alpha = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} ls^j(c_0, c_i)^2 w_j^o (w_j^s + w_j^o)}{\sum_{i=1}^{m} \sum_{j=1}^{n} ls^j(c_0, c_i)^2 (w_j^s + w_j^o)^2} \tag{10}$$

$$\beta = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} ls^j(c_0, c_i)^2 w_j^s (w_j^s + w_j^o)}{\sum_{i=1}^{m} \sum_{j=1}^{n} ls^j(c_0, c_i)^2 (w_j^s + w_j^o)^2} \tag{11}$$

4.2.3. Global similarity measurement

The global similarity refers to the similarity between two cases obtained by integrating the local similarities of all the attributes. Various methods have been proposed for global similarity, including linear and nonlinear methods [33]. In this research, the linear method was adopted. The global similarity between the target case and previous case can be calculated by Eq. (12).

$$\overrightarrow{ls_{(c_0,c_i)}^{j}} \times \overrightarrow{w} = \overrightarrow{gs_{(c_0,c_i)}}, \tag{12}$$

where $\overrightarrow{ls_{(c_0,c_i)}^{j}}$ is the vector of the local similarity of each attribute between the target case and previous case i. The vector $\overrightarrow{w}$ represents the weightings of all attributes, while $\overrightarrow{gs_{(c_0,c_i)}}$ is the final global similarity between the target case and previous case i.

4.3. Case reuse

The application of the retrieved case includes the case reuse and case revision [20]. The corresponding retrofit strategies are all attached to each retrieved case. Thus, these strategies can be obtained when the most similar cases have been identified. In the case retrieval part, more than one case will be selected. However, owing to the fact that each building has its own distinctive features, it is nearly impossible to find a building that is identical to the target building in which retrofitting will be implemented [19]. Thus, the experiences retrieved from the top similar cases are all useful references for the decision makers of the target building.

4.4. Case revision

The manner in which to apply the strategies in the retrieved cases to the target building, and whether they are the best retrofit strategies, should be determined by the decision makers, according to the stakeholder needs. Following the case retrieval process, the designers and building stakeholders may need to make adaptive adjustments according to the target building features. It is worth noting that the opinions of stakeholders may play an important role in the design process. For example, the retrofit project budget is normally determined by the building owner, who will pay for the project. The budget will have a significant impact on the final retrofit design. Therefore, retrofit project designers should communicate with stakeholders and make adjustments to meet stakeholder expectations.

5. Application of proposed CBR system

5.1. Establishment of retrofit case database

In China, numerous retrofit cases have been presented in the form of a report or an article, which can be found in the China National Knowledge Infrastructure (CNKI), a cutting-edge academic website in China. Most of these articles provide detailed information on retrofitted buildings. Thus, the CNKI was selected as the data source for collecting retrofit cases. To ensure that the retrofit strategies were up to date, green retrofit cases within the past 10 years in the CNKI were selected for the case database. These cases needed to be represented further by the attributes listed in Table 1. Moreover, several cases did not contain complete information. Following screening, 71 cases were collected for the retrofit case database.

The collected cases were represented using the attributes in Table 1. For crisp attributes, the crisp number can be used directly as the 'value' of the attributes. For categorical attributes, the values can be categorised according to Table 1. The climate zone of each case was not provided, but the city in which the building is located was provided instead. According to the General Rules for Civil Building Design issued by the MOHURD of the People's Republic of China, China can be divided into five climate zones, as illustrated in Fig. 3. The climate zones of the cases in the database can be identified according to the cities in which the cases are located, as indicated in Fig. 3. For the fuzzy linguistic attributes, the fuzzy linguistic term is used to represent the 'value' of the attributes, according to the retrofit case report and design standard for the energy efficiency of buildings in China.

5.2. Case retrieval process

An office building located in Shanghai was selected as the target building. The floor area of this building, originally built in 1975, is 6231.22 m^2. The owner type is a for-profit corporation. The building condition is substandard. The building envelope insulation, HVAC system, lighting system, and water installations are all at the low efficiency level according to the Design Standard for Energy Efficiency of Buildings issued by the MOHURD of the People's Republic of China. The energy consumption per year is currently 236 kWh/m^2. Thus, the owner plans to undertake full retrofitting to improve the energy efficiency of the building. The estimated budget for retrofitting this building is 1.5 million RMB, and the estimated payback period is five years. After reviewing the building, relevant data were collected. The attribute values were identified based on the collected data, as indicated in Table 3. Then, the CBR method was used to match the cases in the database to identify similar cases and retrieve useful information. The procedure is as follows.

Table 3
Values of attributes in target retrofit case.

Attribute	Target case	Attribute	Target case	Attribute	Target case
A1	1975	B1	Low	C1	236 kWh/m^2
A2	Office	B2	Low	C2	1.5 million RMB
A3	For-profit corporation	B3	Low	C3	5 years
A4	6231.22 m^2	B4	Low		
A5	Hot summer & cold winter				

Step 1: Local similarity measurement

The similarity between the target case and cases in the database could be calculated according to Eqs (1)–(3).

Step 2: Determination of weightings

The stakeholders of the building and nine experts from the Shanghai Architectural Design Institute were invited to determine the weights of all attributes. In this part, the two-level AHP method was used to obtain the subjective weights. When obtaining their decision matrix, all of the decision makers were separated from one another. Based on the attributes selected, pair-wise comparisons of the first-level attributes (general information, component information, and energy and cost information) were first performed. Then, pair-wise comparisons of the second-level attributes were conducted. All of these matrices passed the consistency test with $C.R. = 0.0031$, 0.0997, 0.0468, and 0.0158. Finally, the subjective weights were calculated by these matrices, as indicated in Table 4. The objective attribute weightings were calculated according to the data in the case database and Eqs. (6)–(8), as indicated in Table 4. According to Eqs. (9)–(11), the coefficients α and β could be obtained, with $\alpha = 0.326478$ and $\beta = 0.673522$. The final weightings could be determined by $w = \alpha w^s + \beta w^o$, and the results are presented in Table 4.

Table 4
Weightings of building retrofit attributes.

	A1	A2	A3	A4	A5	B1	B2	B3	B4	C1	C2	C3
FSW	0.01	0.07	0.02	0.03	0.05	0.03	0.20	0.08	0.02	0.11	0.07	0.3
FOW	0.04	0.33	0.15	0.01	0.18	0.06	0.03	0.05	0.04	0.07	0.02	0.02
FW	0.03	0.24	0.11	0.01	0.14	0.05	0.09	0.06	0.04	0.09	0.04	0.11

Note: FSW = final subjective weighting; FOW = final objective weighting; FW = final weighting.

Step 3: Global similarity measurement

According to Eq. (12), the global similarities between each previous retrofit case and the target case were obtained, as indicated in Table 5.

5.3. Case retrieval and adaptation

The top four cases with high global similarity were identified by means of the CBR system. These were cases 58, 23, 51, and 48, with global similarities of 0.923, 0.911, 0.907, and 0.902, respectively. The four cases were first presented to the nine stakeholders of the target building. They all believed that the four cases had strong similarities with the target building, and the experiences from the retrieved past cases could provide a reference for the target building retrofit. The target case had the highest similarity with case 58; both of these are located in Shanghai and both are office buildings. The HVAC system, lighting system, and building envelope of both buildings are in a poor condition. Therefore, the retrofit strategies used in case 58 could be a useful reference for the target building. Cases 23, 51, and 48 also have certain similar attributes to the target case. For example, cases 23 and 48 have similar built years as the target case, namely in the 80s and 90s of last century. Moreover, their building styles and structures are similar. The experiences from cases 23, 51, and 48 may be useful for target building and supplementing case 58. For example, case 51 adopted flush valve diaphragms and aerators for a reduction in water use, which can be considered for application in the target case. With reference to the four similar cases, possible retrofit strategies for the target building are summarised in Table 6.

The information retrieved from the four cases will be presented to decision makers for reference in the future design process. Moreover, the retrofit strategies of the four cases should be examined further for adaptation. Taking case 58 as an example, an intelligent lighting control system was installed to improve the lighting system energy efficiency, while thicker insulating glass was installed to improve the building envelope energy-efficient performance. These strategies can be further considered for use in the target building by the designer. Before applying the same strategies in the target case, certain adjustments may be required, according to the actual conditions of the target building. For example, the target building could adopt an intelligent lighting control system, which needs to be designed effectively to fit the target building.

6. Conclusions

The building sector is a major contributor to energy consumption and greenhouse gas emissions. Compared to new buildings, green retrofitting of existing buildings provides an effective and rapid solution for meeting the energy and greenhouse gas emission goals. However, the decision process of green retrofitting is not easy, because each building exhibits its own characteristics. Most existing research has focused on mathematical modelling. This study has introduced a CBR approach to identify the most similar building retrofit cases for a target building retrofit case. The experience and lessons extracted from the similar cases can be used as a valuable reference for decision makers to gain an improved understanding of the project and make better decisions.

In this study, the building attributes were grouped into three categories, namely general building information, building component information, and energy and cost information. Using the identified attributes, 71 retrofit cases in China were collected and stored in a case database. The AHP–entropy method was adopted to determine the attribute weights. To demonstrate the application of the CBR approach, an office building in Shanghai was selected as a case study. The results indicate that the CBR approach can aid in identifying the most similar cases from the database and extracting useful information for new retrofit projects. The experience or lessons gained from similar cases can be used to improve the decision-making process of new retrofit projects. The limitation of this study is that the case database contains only 71 cases, and that only 12 attributes are used to represent the features of retrofit projects. This may affect the validation accuracy of the approach presented in this study. In future research, additional

Table 5
Global similarity measurement results.

Case	Similarity	Case	Similarity	Case	Similarity	Case	Similarity	Case	Similarity
1	0.566	16	0.417	31	0.578	46	0.363	61	0.584
2	0.500	17	0.735	32	0.184	47	0.741	62	0.548
3	0.377	18	0.461	33	0.440	48	0.902	63	0.567
4	0.571	19	0.473	34	0.631	49	0.668	64	0.876
5	0.471	20	0.732	35	0.413	50	0.722	65	0.773
6	0.302	21	0.433	36	0.639	51	0.907	66	0.671
7	0.698	22	0.329	37	0.399	52	0.489	67	0.847
8	0.270	23	0.911	38	0.705	53	0.339	68	0.674
9	0.363	24	0.737	39	0.588	54	0.765	69	0.375
10	0.869	25	0.811	40	0.596	55	0.634	70	0.771
11	0.315	26	0.641	41	0.572	56	0.555	71	0.582
12	0.451	27	0.502	42	0.515	57	0.444		
13	0.659	28	0.304	43	0.497	58	0.923		
14	0.707	29	0.326	44	0.730	59	0.658		
15	0.452	30	0.572	45	0.576	60	0.691		

Table 6
Retrofit strategies for target building with reference to similar cases.

Retrofit strategies	Reference cases
Replace fluorescent tubes with LED tubes	58, 48, 23
Install intelligent lighting control system	58
Double-glazing of existing windows	58, 23
Change water chiller in existing HVAC system	58, 23, 51
Install chiller group control system in HVAC system	58
Roof insulation	23
Window insulation film	48
Install frequency conversion control system in HVAC system	48
Replace flush valve diaphragms and aerators	51

cases can be collected and grouped into different categories, such as minor retrofit, major retrofit, and deep retrofit. A comprehensive attribute list can be developed to suit different retrofit projects. Consequently, the accuracy of using the CBR approach in assisting the decision-making for building green retrofit can be further improved.

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