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Green decoration materials selection under interior environment characteristics: A grey-correlation based hybrid MCDM method

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ABSTRACT

Materials selection, as a essential link for manufacturing enterprises, has an important driving-force to comprehensively upgrade material properties and service life, especially in building and decoration fields. To qualitatively select the optimal green decoration materials, a hybrid multi-criteria decision making (MCDM) approach integrating analytical hierarchy process (AHP) and grey correlation technique for order performance by similarity to ideal solution (GC-TOPSIS) is proposed. The weights vector of hierarchical index structure, which is established based on interior environmental characteristics, i.e., physiological comfort, psychological satisfaction and interior environmental effect, is determined by AHP. GC-TOPSIS is applied to obtain the final ranking of green decoration materials to select the optimal one. A case study, i.e., 10 kinds of solid woods, is illustrated to validate the proposed method. Additionally, a sensitivity analysis of nine experiments is carried out to monitor the robustness of solution ranking to changes. The results proved that this method furnishes an rational and efficient decision support tool for performance assessment of green decoration materials.

1. Introduction

Material selection plays a significant role in the entire design and manufacturing process for diverse engineering applications, and it has attracted many researchers in recent years [1–5]. Improper selection of materials may negatively affect the performance and service life of products, even result in enormous cost of involvement and ultimately drive towards premature component/product obsolescence [6]. Current materials selection researches can be summed up in three major issues: construct a reasonable hierarchical structure based on various principles/criteria, prioritize and assign weights to relevant criteria, and assessment process of each material alternative. As an important strategy in the industrial system, it has been applied to various fields, especially in building and decoration fields [7,8].

Rapid urbanization and economic globalization strength the rate of manufacturing and infrastructure construction, and make the construction industry become one of the fastest developing sectors in China [1]. Correspondingly, the increasing requirements for the quality of daily life, the aesthetics and comfort level of adornment space/environment for individuals put forward higher demands to the interior environment characteristics for green decoration materials. Interior environment characteristics as one of the most important properties of building decoration materials involves several aspects, i.e., the physiological comfort and satisfaction degree of material properties to individual, building physical conditions and living environment characteristics. Therefore, this paper establishes a hierarchy structure about assessment indicators/criteria focusing on interior environment characteristics, which can be applied in the assessment process of green decoration materials selection.

The process of material alternatives' evaluation is the fundamental basis for green decoration materials selection, but various selection criteria and complex relationships between them make it a challenging task. For instance, when considering interior environment characteristics, some internal criteria, e.g., visual, acoustic, tactile, olfactory, must be taken into account. Therefore, a multi-criteria decision making (MCDM) method become a useful tool to deal with this problem [9,10]. MCDM is divided into five parts: alternatives generation, criteria system building, criteria weights determination, alternatives' assess-

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ment, and application of a ranking system [11]. Each criterion is related to a target in the specific decision framework, and normalization is adopted to transform different criteria into a compatible measurement [12–14]. Technique for order performance by similarity to ideal solution (TOPSIS) approach is considered as one of the commonly used assessment approaches in the practical application. However, it has some shortcomings and drawbacks that need to be improved.

This approach evaluates material alternatives based on the distance relationship among data sequences and merely considers their location relationship among them [15]. For instance, although the index values of each alternative are different from each other, the distance between the primary alternative and positive/negative-ideal one is equal, and their alternative evaluation results are same through TOPSIS/AHP-TOPSIS method. Namely, this MCDM approach is not suitable to assess all kinds of material selection alternatives due to its measurement scale is distance. In fact, to ensure the rationalization and comprehensiveness of the final results, their evaluation not only considers the location relationship among data sequences but also employs the situation/posture changes among data sequences. Instead, grey correlation method takes the similarity of curve shape as a measurement scale, i.e., grey correlation degree, and could be applied to reveal the estimates of situation changes among data sequences [16,17]. To do so, this paper presents a grey-correlation based hybrid MCDM method to evaluate the selection problem of green decoration materials for the first time to the best knowledge of the authors. Compared with the previous researches [18–70], the contributions of this paper could be summarized as three parts: 1) based on the main service object and ergonomics of green decoration materials, a hierarchy structure about assessment criteria focusing on interior environment characteristics is established, and the weights vector of each criterion could be calculated according to AHP method; 2) owing to the defects of TOPSIS approach as described above, a grey-correlation based hybrid MCDM method is presented via a nonlinear programming which is adopted to reduce/avoid subjectivity and irrationality; 3) An empirical application of 10 kinds of solid woods is illustrated. In addition, sensitivity analysis and comparison with existing methods are performed to validate the accuracy and reliability for the proposed hybrid approach.

The structure of this research can be summarized as follows: Section 2 makes a summing up of the literature review. The solution method, i.e., a grey-correlation based hybrid MCDM method, is presented in Section 3. The verification of an empirical case about 10 kinds of solid woods, the comparison of the previous researches, and the sensitivity analysis on variations of criteria weights are presented to demonstrate the new decision framework in Section 4. Section 5 provides a statement about the conclusions and further research topics.

2. Literature review

Materials selection is normally treated as a typical MCDM problem, because of the lack of accurate and formal measurement rules/criteria or programs. Therefore, the assessment process of alternatives is largely established on the basis of reliable experiences from related experts rather than numerical or simulation methods [18–21]. In the literature, many previous researches have explored and proposed various contexts/approaches to carry out the researches of material selection issue, and the adopted impact criteria are social, technical, environmental or economic field [22–26]. Many researches as cases are shown in Table 1 to reveal the particularity of the hierarchy structure about assessment criteria for different material types. However, for different types of materials, the emphasis point should also be distinct. Take this paper as an example, the main service object about green decoration materials is households or work offices. In short, the overall feelings of persons who live/work in the internal environment occupy a large proportion in the selection process for green decoration materials. Therefore, considering interior environment characteristics in the assessment process has an great significance on meeting manufacturing, industrial or practical needs in building field, and contributes to green building standards formulation [27–30].

An overview of main material selection methodologies by the previous researchers is revealed briefly in this section. Overall, this MCDM methods could be summarized into two types: 1) synthetical evaluation methods, e.g., ELimination and Choice Expressing the REality (ELECTRE) [31], TOPSIS [45,46], AHP [30], Vlse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) [47], Decision Making and Evaluation Laboratory (DEMATEL) [48], grey correlation (GC) [49,50], best-worst method (BWM) [51]; and 2) approaches on the basis of life cycle assessment (LCA) [52]. Additionally, some integrated methods have been successfully presented and applied to deal with the shortcomings of single one. For instance, Liu et al. [20] propose a hybrid MCDM method integrating DEMATEL-based ANP (Analytical network process) and modified VIKOR to improve the reliability of the optimization results, which can help engineering designers to deal with the lack of the interrelated relationships analysis among each criterion in material selection process. Peter et al. [53] applied an integrated approach that combines fuzzy extended AHP and fuzzy synthetic extent analysis method to obtain the ultimate rank/priority of each criterion. Shanian and Savadogo [54] present a material selection problem of highly sensitive components via using MCDM method. In addition, owing to the drawbacks of uncertainty, fuzzy theory and 2-Tuple theory are been coupled in the assessment process [55,56].

The review of the literature illustrates that although there are many effective assess-levels/approaches to deal with the issue of material selection. Nevertheless, some aspects still be overlooked, e.g., interior environment characteristics, which have a significant impact on the assessment process for green decoration materials, is rarely considered; TOPSIS approach as a commonly used decision support tool is not appropriate to evaluate all kinds of material alternatives because its measurement scale is distance. Therefore, a hybrid evaluation approach integrating AHP and GC-TOPSIS is proposed to help fill the gap. The weights vector of hierarchical index structure, which is established based on interior environmental characteristics, i.e., physiological comfort, psychological satisfaction and interior environmental effect, is determined by AHP approach. GC-TOPSIS is applied to obtain the final ranking of green decoration materials to select the optimal one.

3. A grey-correlation based hybrid MCDM method

In this section, a grey-correlation based hybrid MCDM method integrating AHP, GC and TOPSIS is proposed for multi-criteria optimization in complex systems. After generating decoration material alternatives and identifying the material selection criteria system, AHP is applied to determine the weights vector of hierarchy structure about assessment indicators/criteria focus on interior environment characteristics; GC-TOPSIS is adopted to select the optimal material alternative based on integrated closeness index. The proposed comprehensive approach is illustrated step by step as below.

3.1. AHP approach

AHP, introduced by Saaty [71], reveals the principle to obtain the relative importance/weights of several clusters of indexes/criteria to lay the foundation for MCDM problems. A hierarchical structure including different levels and various indexes/criteria, which was formulated based on the characteristics of certain events, could be categorized into three layer, i.e., the target one, the rule one, and the index one [72]. The pair-wise comparison matrix (PWCM) was structured by related experts with reliable experience based on the fundamental scale of comparison values as shown in Table A1, thus calculating the corresponding preference/weight of each decision

Table 1
List of various material selection criteria as proposed by previous researches.

Cluster level	**Material selection**			
	Economic criteria (I)	**Environment criteria (N)**	**Society criteria (S)**	**Technical criteria (X)**
Criterion level	I1: Initial-acquisition cost I2: Maintenance cost I3: Disposal cost I4: Productivity I5: Revenue I6: Meeting user needs I7: Tax contribution	N1: Energy saving N2: Potential for recycling and reuse N3: Raw material extraction N4: Land acquisition N5: Usage of water N6: Waste management N7: CO_2 emission N8: Fuel consumption N9: Ozone depletion potential N10: Fuel consumption	S1: Operational life S2: Esthetics S3: Use of local material S4: Health and safety S5: Labor availability S6: Physical performance	X1: Maintainability ×2: Buildability ×3: Resistance to decay ×4: Life expectancy ×5: Sensible heat storage ×6: Fire resistance
References	[1,6,20,23,28–33,57,58,65,66,69]	[1,12,20,28–31,34–37,58,59,67]	[1,6,20,28,29,38–41,60,63,64,69]	[23,42–44,61,62,68–70]

criterion in the hierarchical structure [73]. Additionally, the analysis procedure not only considers subjective preferences but also integrates expert experience and objective information to ensure the rationality and effectiveness. The basic steps could be summarized into five parts: a) identify the decision problem; b) formulate the fundamental scale about preferences among criteria; c) structure a PWCM A for k decision criteria by related experts as shown in Eqs. (1) and (2); d) obtain the weights vector of each criterion $w = (w_1, w_2,..., w_k)$ in the hierarchical structure according to Eq. (3); e) check consistency based on the final consistency ratio (CR) where $CR = (\lambda_{max} - k) / (RI * (k - 1))$ [74,75]. Note that CI is the consistency indicator and RI is random consistency indicator as shown in Table A2.

$$A = [a_{ij}],\ \ i = 1,\ 2,\ \dots, k;\ j = 1,\ 2,\ \dots, k \tag{1}$$

$$a_{ii} = 1, a_{ij} > 0;\ a_{ji} = 1/a_{ij}, i = 1,\ 2, \dots, k; j = 1,\ 2,\ \dots, k \tag{2}$$

$$Aw = \lambda_{\max} w \tag{3}$$

where w expresses the eigenvector corresponding to the maximal eigenvalue λ_{max} of matrix A.

If $CR < 0.1$, the judgment matrix can be accepted. Otherwise, it is unable to meet the requirements of consistency, which should be reviewed and improved.

3.2. GC-TOPSIS approach

GC is an MCDM approach to evaluate design alternatives via grey relational closeness index [76,77]. It adopts grey relational degree of similarity among data curves as a measurement scale and can be used to estimate situation changes among data sequences [78,79]. Usually, the closer the curve is, the larger the grey relational degree, otherwise, the smaller the grey relational degree. TOPSIS is an MCDM approach which was first proposed by Hwang and Yoon [80]. It adopts the distance relationship among data sequences as a measurement scale, and can be used to estimate the location relationship among them. Their detailed description can refer to [81–83]. The GC-TOPSIS method that combining GC and TOPSIS, which has the following steps:

Step 1: Construct a decision matrix for alternatives under the criteria of the hierarchical structure. The decision matrix $X = [x_{ij}]$ (i = 1, 2, ..., n; j = 1, 2, ..., m) could be gathered via related experts from various fields, e.g., scholars of college and supervisors of enterprise, through questionnaire surveys or investigate. Among them, x_{ij} denotes a certain value expressing the priority level of each alternative i corresponding to each criterion j; n indicates the total number of decision alternatives; m denotes that the total number of criteria in the hierarchical structure.

Step 2: Obtain the normalized-weighted matrix $Z = w^T Y$ combined with the weights vector of criteria. $Y = [y_{ij}]$ (i = 1, 2, ..., n; j = 1, 2, ..., m) expresses the normalized matrix. The standardization process of the decision matrix X is generally divided into two forms based on the property of criteria: for the benefit criteria, the normalized value $y_{ij} = x_{ij}/\max_i x_{ij}$ (i = 1, 2, ..., n; j = 1, 2, ..., m); For the cost criteria, the normalized value $y_{ij} = \min_i x_{ij}/x_{ij}$ (i = 1, 2, ..., n; j = 1, 2, ..., m). Additionally, the weights vector of each criterion $w = (w_1, w_2,..., w_k)$ is obtained via AHP approach.

Step 3: Compute the positive-ideal and negative-ideal solutions, they are denoted as,

$$Z^+ = [z_j^+] = [\max_{1\le i\le n}(\{z_{ij}\}_{i=1}^n)\Big| j \in J^+,\ \min_{1\le i\le n}(\{z_{ij}\}_{i=1}^n)\Big| j \in J^-],$$
$$(j = 1,\ 2,\ \dots, m) \tag{4}$$

$$Z^- = [z_j^-] = [\min_{1\le i\le n}(\{z_{ij}\}_{i=1}^n)\Big| j \in J^+,\ \max_{1\le i\le n}(\{z_{ij}\}_{i=1}^n)\Big| j \in J^-],$$
$$(j = 1,\ 2,\ \dots, m) \tag{5}$$

where J^+ denotes the indicator type which the greater the better. J^- denotes the indicator type which the smaller the better.

Step 4: Compute the grey correlation coefficient between ith alternative and positive/negative-ideal alternative about jth index. Note that "*" represents "+" or "-".

$$\mathrm{r}_{ij}^* = \frac{\min_i \min_j |z_j^* - z_{ij}| + \rho \max_i \max_j |z_j^* - z_{ij}|}{|z_j^* - z_{ij}| + \rho \max_i \max_j |z_j^* - z_{ij}|} \tag{6}$$

where $\rho \in [0,1]$ denotes the resolution factor. As a general rule, $\rho = 0.5$.

The grey correlation coefficient matrix about each alternative and positive/negative-ideal alternative can be expressed as $R^* = [r_{ij}^*]$ (i = 1, 2, ..., n; j = 1, 2, ..., m). The grey correlation degree between ith alternative and positive/negative-ideal alternative can be obtained according to Eq. (7).

$$R_i^* = \frac{1}{m}\sum_{j=1}^{m} r_{ij}^*,\ \ (i = 1,\ 2,\ \dots, n) \tag{7}$$

Step 5: Compute the separation measures based on the dimensional Euclidean distance. The separation of each alternative from the positive/negative-ideal solution D_i^* can be computed as

$$D_i^* = \sqrt{\sum_{j=1}^{m} [z_{ij} - z_j^*]^2},\ \ (i = 1,\ 2,\ \dots, n) \tag{8}$$

Step 6: Apply dimensionless method to the R_i^+, R_i^-, D_i^+ and D_i^-, respectively.

The normalized value $\tilde{\theta}_i$ is computed as

$$\tilde{\theta}_i = \frac{\theta_i}{\max_{1\le i\le n} \theta_i},\ \ (i = 1,\ 2,\ \dots, n) \tag{9}$$

where θ_i represents the R_i^+, R_i^-, D_i^+ and D_i^-; $\tilde{\theta}_i$ represents the $\tilde{R}_i^+$, $\tilde{R}_i^-$,

$\widetilde{D}_i^+$ and $\widetilde{D}_i^-$.

Step 7: Calculate the similarity closeness index and the distance closeness index.

$$\widetilde{R}_i = \frac{\widetilde{R}_i^+}{\widetilde{R}_i^+ + \widetilde{R}_i^-}, \quad (i = 1, 2, \ldots, n) \tag{10}$$

$$\widetilde{D}_i = \frac{\widetilde{D}_i^-}{\widetilde{D}_i^+ + \widetilde{D}_i^-}, \quad (i = 1, 2, \ldots, n) \tag{11}$$

Clearly, $\widetilde{D}_i$ and $\widetilde{R}_i$ are certain values between 0 and 1. Based on the assessment principles for this two approaches, the larger the similarity closeness index ($\widetilde{R}_i$)/the distance closeness index ($\widetilde{D}_i$), the better the performance of green decoration material.

Step 8: Obtain the ultimate decision index by a nonlinear programming model. To reduce the subjectivity of the integration process, a nonlinear programming model is proposed to compute the ultimate decision index CS_i (the integrated closeness index), which is the basis of the final rank of material alternatives. Compared with the traditional weighted-integration method, the results obtained from this model reduce the subjectivity of decision makers. The nonlinear programming model with constraints can be formulated as

$$\left\{\begin{array}{l} \min \sum_{i=1}^{n} [(\xi_i)^2 + (\delta_i)^2] \\ \xi_i = CS_i - \widetilde{R}_i \\ \delta_i = CS_i - \widetilde{D}_i \\ s.\ t.\ \ \min(\widetilde{R}_i, \widetilde{D}_i) \le CS_i \le \ \max(\widetilde{R}_i, \widetilde{D}_i) \\ \ \ 0 < CS_i < 1 \end{array}\right. , \quad (i = 1, 2, \ldots, n) \tag{12}$$

3.3. The integrated assessment process for decoration material selection

This work proposes a grey-correlation based hybrid MCDM method that integrates AHP and GC-TOPSIS, which considers the interior environment characteristics as assessment hierarchical structure. This approach takes full advantage of the quantitative and comprehensive analysis features and overcomes the defect of TOPSIS/AHP-TOPSIS approach in a decision process. In addition, it effectively reduces the subjectivity of the integrated method via a nonlinear programming. The procedure of this hybrid method can be summarized into two stages, as shown in Fig. 1.

Stage 1: Compute the weights vector of hierarchical structure/criteria according to AHP approach

Based on the different criteria of the formulated hierarchical structure, the PWXM are structured by related experts with reliable experience by referring to the fundamental scale of comparison values as shown in Table A1. Note that the final PWXM is established by calculating the mathematic average for the quantitative values of the matrixes acquired from each expert. Thus, the corresponding preference/weight of decision criteria can be computed by the process of AHP. Additionally, check consistency is required to verify the validity of the results. The judgment matrix and the weights vector of each criterion $w = (w_1, w_2, \ldots, w_k)$ can be accepted and applied in the following calculation only when $CR <$ 0.1.

Stage 2: Select the optimal decoration material by GC-TOPSIS

The decision matrix for alternatives is established by calculating the mathematic average for the quantitative values of the matrixes acquired from each expert. The ultimate rank of the integrated closeness index can be obtained via the calculation process of this hybrid approach, i.e., GC-TOPSIS. Thereby, the optimal green decoration material is selected based on the results. In addition, the nonlinear programming model can be calculated by complex/penalty function method. In this paper, complex method is applied to obtain the integrated closeness index CS_i under the MATLAB platform. Note that the larger the similarity closeness index ($\widetilde{R}_i$)/the distance closeness index ($\widetilde{D}_i$), the better the performance of green decoration material. Therefore, the larger the value of CS_i, the better the performance of the green decoration material alternatives.

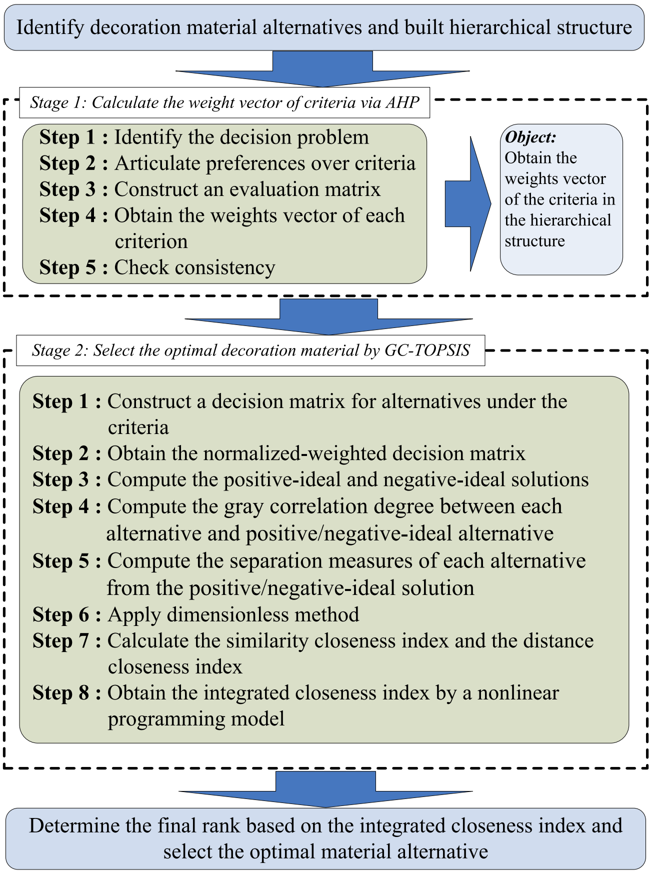

Fig. 1. The framework of the hybrid MCDM method.

4. Empirical example

An empirical research is displayed to illustrate the application of this hybrid MCDM approach to evaluate green decoration material alternatives and select the optimal one in real world case. Sensitivity analysis and comparison with existing methods are performed to validate the accuracy and reliability for this method.

4.1. Background

Considering the characteristics of economic, environmental protection and aesthetics, solid woods has becoming the most common decorative material in build field. After preliminary screening, ten kinds of solid woods, i.e., Juglans mandshurica, Quercus mongolica, fraxinus mandshuric, Pterocarpus santalinus, Betula platyphylla, larix gmelini, picea jezoensis var.microsperma, abies nephrolepis, Pinus koraiensis and Pinus sylvestris var. mongolica, are regarded as green decoration material alternatives in empirical example.

As shown in Section 2, many quantitative and qualitative criteria should be considered/added into the hierarchical structure, which is applied to determine the optimal decoration material alternative, e.g., initial-acquisition cost, health and safety and fire resistance. For different types of materials, the emphasis point should also be distinct [84–86]. In this section, interior environment characteristics are organized into a hierarchical structure with three levels, i.e., goal, criterion and sub-criterion levels. As shown in Fig. 2, goal level (E) is

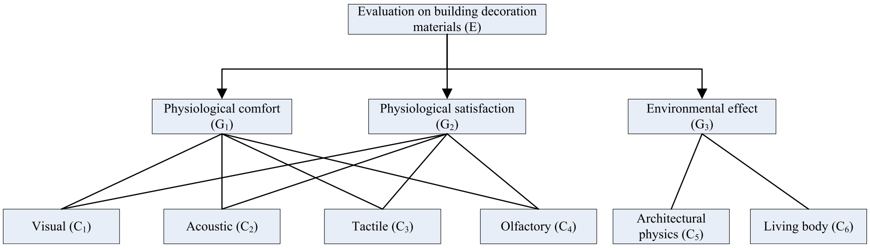

Fig. 2. Hierarchical structure of interior environmental characteristics of building decoration materials.

evaluation on green decoration materials; criterion level (G) is physiological comfort (G_1), physiological satisfaction (G_2) and environmental effect (G_3); physiological comfort includes four criteria, i.e., visual (C_1), acoustic (C_2), tactile (C_3), olfactory (C_4); physiological satisfaction includes four criteria, i.e., visual (C_1), acoustic (C_2), tactile (C_3), olfactory (C_4); environmental effect includes two criteria, i.e., architectural physics (C_5), living body (C_6).

Initial data and related information can be gathered by experts from various fields, e.g., scholars of college and supervisors of enterprise, through questionnaire surveys. In this research, eight experts, including three scholars who specialize in material selection, three supervisors from related companies with a good reputation, and two customers who have used these products for over three years, were interviewed to obtain the pair-wise comparison matrix of each criterion and the decision matrix for the selection of optimal material. Due to space limitation, the final matrixes are only given here as shown in Tables A3–A6 and Table 3. This investigation was conducted in June 2015.

4.2. Determination of the weights vector of criteria based on AHP approach

The weights vector of each decision criterion has a great influence on decision-making of green decoration materials. Thus, this work applies AHP approach to obtain the weights vector of each criterion/factor of interior environmental characteristics. The basic steps could be summarized into two parts as follows:

1) Establish PWCM

   The PWCM from interior environmental characteristics evaluation of view (E-G) was structured by related experts with reliable experience based on the fundamental scale of comparison values, which is demonstrated in Table A3. In the same way, the PWCMs from physiological comfort perspective (G_1-C), from physiological satisfaction perspective (G_2-C), and from environmental effect perspective (G_3-C) are presented in Tables A4–A6, respectively.
2) Criterion/factor importance degree and CR test

   Based on the calculation process of AHP, the weights vector of each criterion/factor in the hierarchical structure and the value of *CR* can be computed. The importance of each criterion and its *CR* of each PWCM are shown in Tables A7–A10, respectively. Additionally, the ultimate weights vector of criteria on overall goal of evaluation index can be obtained, which is presented in Table 2.

Table 2
Weights of each criterion and rank on overall goal.

Criteria	Overall weights	Rank
Visual (C_1)	0.42	1
Acoustic (C_2)	0.06	5
Tactile (C_3)	0.18	3
Olfactory (C_4)	0.25	2
Architectural physics (C_5)	0.02	6
Living body (C_6)	0.06	4

Table 3
Score of each criterion for material alternatives.

Alternatives	C_1	C_2	C_3	C_4	C_5	C_6
Juglans mandshurica (Alternative 1)	6	4	7	5	7	5
Quercus mongolica (Alternative 2)	6	5	5	5	7	5
Fraxinus mandshuric (Alternative 3)	7	6	5	5	7	5
Pterocarpus santalinus (Alternative 4)	7	6	5	7	7	6
Betula platyphylla (Alternative 5)	5	6	6	5	7	5
Larix gmelini (Alternative 6)	6	6	5	6	7	5
Picea jezoensis var.microsperma (Alternative 7)	5	7	7	6	7	5
Abies nephrolepis (Alternative 8)	6	4	7	5	7	5
Pinus koraiensis (Alternative 9)	6	5	6	6	7	6
Pinus sylvestris var. mongolica (Alternative 10)	6	5	6	6	7	5

4.3. Evaluation of green decoration materials' green performance

Based on expert interview and related literature review [23,56,84], the score of each criterion for green decoration material alternatives is listed in Table 3. The final rank of the integrated closeness index can be obtained via the calculation process of this hybrid approach, i.e., GC-TOPSIS. Thereby, selecting the optimal green decoration material based on the results. The concrete procedure for the assessment of empirical example, i.e., ten kinds of solid woods, is shown below:

1) Based on Table 3, the decision matrix $X = [x_{ij}]$ ($i = 1, 2, ..., n$; $j = 1, 2, ..., m$) for alternatives under the criteria of the hierarchical structure is established as

$$X = \begin{bmatrix} 6 & 4 & 7 & 5 & 7 & 5 \\ 6 & 5 & 5 & 5 & 7 & 5 \\ 7 & 6 & 5 & 5 & 7 & 5 \\ 7 & 6 & 5 & 7 & 7 & 6 \\ 5 & 6 & 6 & 5 & 7 & 5 \\ 6 & 6 & 5 & 6 & 7 & 5 \\ 5 & 7 & 7 & 6 & 7 & 5 \\ 6 & 4 & 7 & 5 & 7 & 5 \\ 6 & 5 & 6 & 6 & 7 & 6 \\ 6 & 5 & 6 & 6 & 7 & 5 \end{bmatrix}$$

2) Obtain the normalized-weighted matrix $Z = w^T Y$ combined with the weights vector of each criterion as shown in Table A11. Thus, the positive-ideal/negative-ideal solutions can be calculated, which are presented in Table A12.
3) The grey correlation coefficient matrix and the grey association degree can be obtained according to Eqs. (4)–(7). The separation of alternatives from D_i^+ and D_i^- could be computed according to Eq. (8). The normalized values $\widetilde{R}_i^+$, $\widetilde{R}_i^-$, $\widetilde{D}_i^+$ and $\widetilde{D}_i^-$ according to Eq. (9) are:

$$\widetilde{R}_i^+ = (0.7609,\ 0.6580,\ 0.8181,\ 1.0000,\ 0.6966,\ 0.7314,\ 0.8651,\ 0.7609,\ 0.7826,\ 0.7403)$$

$$\widetilde{R}_i^- = (0.8974,\ 0.9837,\ 0.9284,\ 0.7481,\ 1.0000,\ 0.8433,\ 0.8298,\ 0.8974,\ 0.7437,\ 0.7857)$$

$$\widetilde{D}_i^{+} = (0.6822,\ 0.7598,\ 0.6241,\ 0.3656,\ 1.0000,\ 0.5993,\ 0.8698,\ 0.6822,\ 0.5172,\ 0.5220)$$

$$\widetilde{D}_i^{-} = (0.5602,\ 0.4297,\ 0.8594,\ 1.0000,\ 0.2191,\ 0.5320,\ 0.5034,\ 0.5602,\ 0.5569,\ 0.5524)$$

4) The similarity closeness index and the distance closeness index are acquired according to Eqs. (10) and (11); and the integrated closeness index is gained using a nonlinear programming model with constraints as shown in Step 8, and the final rank can be obtained. The integrated closeness index and final rank are shown in follows: the integrated closeness index for Juglans mandshurica is 0.4548, the integrated closeness index for Quercus mongolica is 0.3810, the integrated closeness index for fraxinus mandshuric is 0.5239, the integrated closeness index for Pterocarpus santalinus is 0.6522, the integrated closeness index for Betula platyphylla is 0.2952, the integrated closeness index for larix gmelini is 0.4674, the integrated closeness index for picea jezoensis var.microsperma is 0.4385, the integrated closeness index for abies nephrolepis is 0.4548, the integrated closeness index for Pinus koraiensis is 0.5156, and the integrated closeness index for Pinus sylvestris var. mongolica is 0.4996, i.e., Pterocarpus santalinus > fraxinus mandshuric > Pinus koraiensis > Pinus sylvestris var. mongolica > larix gmelini > abies nephrolepis = Juglans mandshurica > picea jezoensis var.microsperma > Quercus mongolica > Betula platyphylla, as shown in Table 4.

4.4. Comparison of the obtained results

In this work, AHP-TOPSIS method and GC method are applied to compare the outcomes of the integrated approach. Note that the same weight is adopted when using three MCDM approaches. Table 4 expresses the assessment results of closeness index obtained from three decision approaches.

From Table 4, some results can be summarized that the ultimate rank obtained from three approaches are adjacent and coincide basically. Some conclusions can be obtained that this grey-correlation-based hybrid MCDM method is reasonable and feasible to select optimal decoration material alternative in building field. According to the results from these approaches, Pterocarpus santalinus is the optimal green decoration material considering interior environment characteristics as hierarchical structure. In addition, the ranks of decoration material alternatives are distinct. For instance, Picea jezoensis var.microsperma is ranked fourth via AHP-GC approach, but was ranked eighth via AHP-TOPSIS. Several reasons of this discrepancy are summarized as follows: 1) the degree of information utilization is different in different information aggregation methods, and a large amount of information can be easily lost in the aggregation process; 2) the principium of TOPSIS is based on the distance from the positive/negative-ideal solution rather than consider the degree of similarity to the ideal solution; and 3) similarly, GRA only considers the degree of similarity to the ideal solution, thereby easily resulting in information loss. Therefore, we propose a grey-correlation based hybrid MCDM method to select the optimal green decoration material logically and effectively. In addition, nonlinear programming is applied to reduce the subjectivity of the decision-making process.

Table 4
Comparison results obtained from three approaches.

Alternatives	**AHP-TOPSIS method**		**The proposed method**		**AHP-GC method**	
	D_i	**Order**	CS_i	**Order**	R_i	**Order**
Juglans mandshurica	0.4509	6	0.4548	6	0.4588	7
Quercus mongolica	0.3612	9	0.3810	9	0.4008	10
Fraxinus mandshuric	0.5793	2	0.5239	2	0.4684	5
Pterocarpus santalinus	0.7323	1	0.6522	1	0.5721	1
Betula platyphylla	0.1797	10	0.2952	10	0.4106	9
Larix gmelini	0.4702	5	0.4674	5	0.4645	6
Picea jezoensis var.microsperma	0.3666	8	0.4385	8	0.5104	3
Abies nephrolepis	0.4509	6	0.4548	6	0.4588	7
Pinus koraiensis	0.5185	3	0.5156	3	0.5127	2
Pinus sylvestris var. mongolica	0.5142	4	0.4996	4	0.4851	4

4.5. Sensitivity analysis

Nine experiments are done to verify the influence of the weights vector of criteria for the ultimate results/ranks (denoted by ω_{Ci} for criteria C_i where i =1, 2, ..., n). The results of their experiments are listed in Table 5. Fig. 3 presents the results of sensitivity analysis for the nine experiments (the integrated closeness index CS_i scores can be found from Table 5).

It can be summarized from Table 5 and Fig. 3 that out of nine experiments, alternative 4 (pterocarpus santalinus) has the highest score in 6/9 experiments. Hence, the final result for optimal material selection of the ten material alternatives is relatively sensitive to the criteria weights. In addition, the ultimate rank of the alternatives changes greatly with the weight varies of each criterion. Therefore, obtaining the weight of each criterion reasonably and scientifically plays a significant role in the selection of the optimal green material.

5. Conclusions

Selecting the optimal green decoration material is a difficult and restrained task for the building field. This paper formulated a hierarchical structure with interior environment characteristics, i.e., visual, acoustic, tactile, olfactory architectural physics and living body, and presented a grey-correlation based hybrid MCDM approach that integrates AHP, GC and TOPSIS to handle the defects and deficiencies of single method. An empirical application of 10 kinds of solid woods was illustrated. The results of comparison with existing methods validated the accuracy and reliability for the proposed hybrid approach. In addition, the research of sensitivity analysis revealed that obtaining the weight of each criterion reasonably and scientifically plays a significant role in the selection of the optimal green material. Therefore, this grey-correlation based hybrid MCDM approach is an effective and accurate tool for green decoration materials selection.

In the future, our studies will focus on two direction: 1) considering other critical influences, i.e., social, technical, environmental or economic factors, formulate a more comprehensive hierarchical structure for material selection; 2) owing to the information of experts in the decision matrix has an uncertain and fuzzy feature, uncertain theory needs to be integrated in the MCDM approaches to fill the gap [87–95].

Table 5
Nine experiments for sensitivity analysis.

Exp. no.	Definition	CS_1	CS_2	CS_3	CS_4	CS_5	CS_6	CS_7	CS_8	CS_9	CS_{10}
1	$\omega_{C1} = 0.625$, $\omega_{C2\text{-}C6} = 0.075$	0.4735	0.4616	0.6734	**0.7230**	0.2762	0.4893	0.3361	0.4735	0.5017	0.4881
2	$\omega_{C2} = 0.625$, $\omega_{C1,C3\text{-}C6} = 0.075$	0.2689	0.3987	0.5747	0.5981	0.5676	0.5771	**0.7270**	0.2688	0.4225	0.4145
3	$\omega_{C3} = 0.625$, $\omega_{C1\text{-}C2,C4\text{-}C6} = 0.075$	**0.6595**	0.2558	0.3058	0.3512	0.4829	0.3006	0.7156	**0.6595**	0.5096	0.4961
4	$\omega_{C4} = 0.625$, $\omega_{C1\text{-}C3,C5\text{-}C6} = 0.075$	0.2813	0.2520	0.3020	**0.7268**	0.2800	0.5318	0.5558	0.2813	0.5446	0.5312
5	$\omega_{C5} = 0.625$, $\omega_{C1\text{-}C4,C6} = 0.075$	0.4002	0.3269	0.4602	**0.6114**	0.4023	0.4617	0.5709	0.4002	0.5150	0.4484
6	$\omega_{C6} = 0.625$, $\omega_{C1\text{-}C5} = 0.075$	0.3036	0.2590	0.3323	**0.7078**	0.2994	0.3252	0.3882	0.3036	0.6731	0.3135
7	$\omega_{C1\text{-}C6} = 0.167$	0.4002	0.3269	0.4602	**0.6114**	0.4023	0.4617	0.5709	0.4002	0.5150	0.4484
8	$\omega_{C1\text{-}C4} = 0.25$, $\omega_{C5\text{-}C6} =0$	0.4166	0.3456	0.4794	0.5809	0.4224	0.4853	**0.5948**	0.4166	0.4722	0.4722
9	$\omega_{C1\text{-}C4} = 0$, $\omega_{C5\text{-}C6} = 0.5$	0.2298	0.2298	0.2298	**0.7702**	0.2298	0.2298	0.2298	0.2298	**0.7702**	0.2298

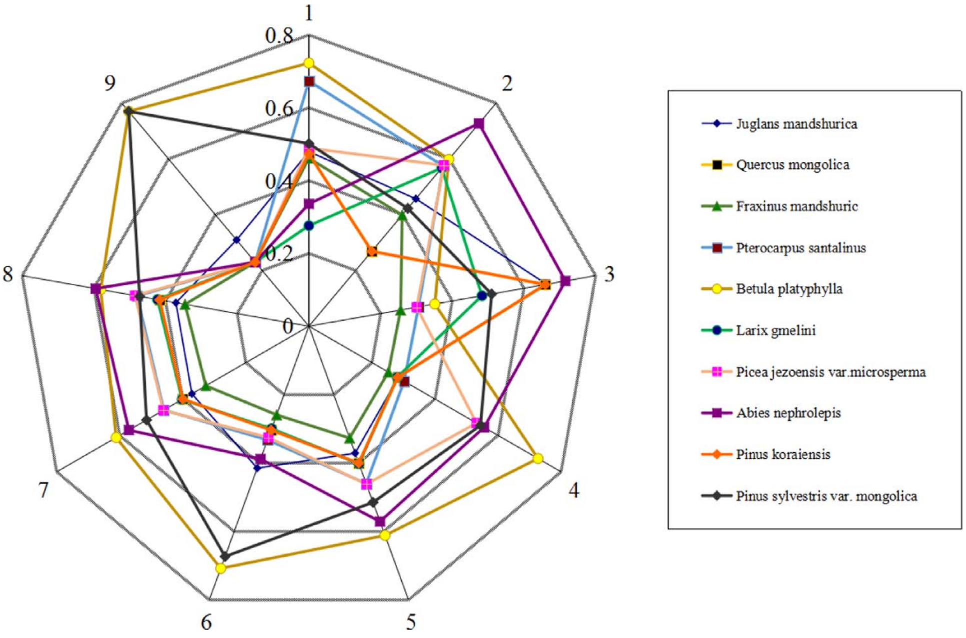

Fig. 3. The results of sensitivity analysis.

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Appendix

See Tables A1–A12.

Table A1
AHP scale for combinations.

Numerical scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one over another
5	Strong importance	Experience and judgment strongly favor one over another
7	Very strong importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	Importance of one over another affirmed on the highest possible order
2, 4, 6, and 8	Intermediate values	Used to represent compromise between the priorities listed above
Reciprocals ($1/a_{ij}$)	A value attributed when activity *i* is compared to activity *j* becomes the reciprocal when *j* is compared to *i*	

Table A2
Random consistency index (*RI*).

k	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table A3
PWCM from interior environmental characteristics evaluation of view (E-G).

	G_1	G_2	G_3
G_1	1	1/5	3
G_2	5	1	7
G_3	1/3	1/7	1

Table A4
PWCM from physiological comfort perspective (G_1-C).

	C_1	C_2	C_3	C_4
C_1	1	1/3	1/7	1/5
C_2	3	1	1/6	1/6
C_3	7	6	1	2
C_4	5	6	1/2	1

Table A5
PWCM from physiological satisfaction perspective (G_2-C).

	C_1	C_2	C_3	C_4
C_1	1	7	6	3
C_2	1/7	1	1/3	1/5
C_3	1/6	3	1	1/3
C_4	1/3	5	3	1

Table A6
PWCM from environmental effect perspective (G_3-C).

	C_5	C_6
C_5	1	1/3
C_6	3	1

Table A7
Criteria weight and *CR* from interior environmental characteristics evaluation of view (E-G).

Criteria	Weight	Rank
Physiological comfort (G_1)	0.19	2
Physiological satisfaction (G_2)	0.72	1
Environmental effect (G_3)	0.08	3
CR	$0.057 < 0.1$	

Table A8
Factor weight and *CR* from physiological comfort perspective (G_1-C).

Factors	Weight	Rank
C_1	0.06	4
C_2	0.10	3
C_3	0.51	1
C_4	0.33	2
CR	$0.077 < 0.1$	

Table A9
Factor weight and *CR* from physiological satisfaction perspective (G_2-C).

Factors	Weight	Rank
C_1	0.57	1
C_2	0.06	4
C_3	0.11	3
C_4	0.26	2
CR	$0.047 < 0.1$	

Table A10
Factor weight and *CR* from environmental effect perspective (G_3-C).

Factors	Weight	Rank
C_5	0.25	2
C_6	0.75	1

Table A11
The normalized decision matrix *Z*.

	C_1	C_2	C_3	C_4	C_5	C_6
Juglans mandshurica	2.52	0.24	1.26	1.25	0.14	0.3
Quercus mongolica	2.52	0.3	0.9	1.25	0.14	0.3
Fraxinus mandshuric	2.94	0.36	0.9	1.25	0.14	0.3
Pterocarpus santalinus	2.94	0.36	0.9	1.75	0.14	0.36
Betula platyphylla	2.1	0.36	1.08	1.25	0.14	0.3
Larix gmelini	2.52	0.36	0.9	1.5	0.14	0.3
Picea jezoensis var.microsperma	2.1	0.42	1.26	1.5	0.14	0.3
Abies nephrolepis	2.52	0.24	1.26	1.25	0.14	0.3
Pinus koraiensis	2.52	0.3	1.08	1.5	0.14	0.36
Pinus sylvestris var. mongolica	2.52	0.3	1.08	1.5	0.14	0.3

Table A12
The positive-ideal and negative-ideal solutions.

	C_1	C_2	C_3	C_4	C_5	C_6
Z_j^+	2.94	0.42	1.26	1.75	0.14	0.36
Z_j^-	2.10	0.24	0.90	1.25	0.14	0.30

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2017.08.050.

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