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Optimal Selection of Eco-Friendly Building Insulation Materials using a Spherical Fuzzy Multi-Criteria Decision Model

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Building insulation materials play an important role in improving the energy efficiency of the construction and building sector. These insulation materials may also have environmental impacts attributed to the use of non-renewable raw materials and fossil-based energy consumption. Waste valorization provides an opportunity to use secondary materials for these building insulation materials. Thus, the selection of sustainable building insulation materials should not only consider the thermal properties such as heat and fire resistance but also environmental factors, among others. This paper proposes a decision modeling approach to optimally select the appropriate building insulation material even at the early design stage where the level of uncertainty will be high. The decision model integrates the Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) with spherical fuzzy sets to model ambiguous human opinion during the evaluation process. A case study is presented to illustrate the method in the prioritization of the insulation materials that include the use of waste materials and geopolymer. Indication suggests a foamed coal fly ash-based geopolymer is ranked 1st among the insulation materials being considered as it performs better in terms of thermal capacitance, embodied carbon and fire rating.

1. Introduction

UNEP reported that the building and construction sector recorded the highest share in global energy demand, 35 % in 2019 (UNEP, 2020) and 36 % in 2020 (UNEP, 2021) and the highest global share of energy related CO_2 emissions, 38 % in 2019 (UNEP, 2020) and 37 % in 2020 (UNEP, 2021). It has been recognized that the highest impact for cost-effective emission reductions can potentially be contributed by the building sector, and that emission reduction targets cannot be met without supporting energy efficiency initiatives in the building sector (UNEP, 2009).

The development of geopolymers as an alternative building material addresses the emerging attention to circular economy and closed-loop systems (La Scalia et al., 2021), reduction in the use of virgin materials (Mohajerani et al., 2019), and sustainable materials and processes (Zhang et al., 2014). Geopolymers, having comparable strength properties to OPC, can be used as a structural material (Ma et al., 2018). It has significant heat and fire resistance (Lahoti et al., 2014) and possesses low thermal conductivity (Emdadi et al., 2014) which merits its adoption for heat flow reduction in the building envelope. Furthermore, life cycle analysis of geopolymers have shown significant achievable reduction in carbon footprint and embodied energy while contributing towards waste valorisation and utilization (Kalaw et al., 2016).

Conventionally, heat flow reduction in or out of the building envelope is achieved via low thermal conductivity structural layers with or without additional insulation layers which carry no structural load. The common type of “add-in layers” insulation materials used in the building and construction sector are generally produced or taken directly from natural resources. This results in depletion of available reserves and to increasing costs (Saygili and Baykal, 2011). The production processes and utilization of these insulation materials such as fiberglass, mineral wool or polyurethane foams also pose health risks to humans (Panyakaew and Fotios, 2011).

The assessment on the use of geopolymers as a heat flow reduction material, either as low thermal conductivity and fire-resistant structural materials or as an “add-in layer” building insulation material, is generally based on

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thermal properties of the geopolymer and the load requirements of the building. However, a deeper evaluation of the sustainability of geopolymers in this application using a multiple criteria assessment method which combines technical, economic, environmental, effect on human health, and others, in comparison with conventional materials, has not been done yet.
This study thus aims to evaluate geopolymer materials vis-à-vis other insulation materials using a decision model that integrates Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) Order of Preference by Similarity to Ideal Solution method with spherical fuzzy set. While AHP is intuitive and flexible in computing priority weights from value judgment, TOPSIS provides more efficient logical technique to rank large number of alternatives and attributes. This technique creates two additional positive and negative ideal alternatives as reference points to guide the decision-maker in choosing the optimal alternative among those considered. Ranking of the alternatives is based on how close the alternative to the positive ideal and how far from the negative ideal in a geometrical sense. AHP and TOPSIS are among the most widely used multi-criteria decision analysis technique as shown by their continuing rapid growth of applications in the literature (Zyoud and Fuchs-Hanusch, 2017). Fuzzy extensions of AHP and TOPSIS are also becoming popular to provide solution in handling uncertain data and ambiguous human opinion in real-life decision-making process in construction and building (Zavadskas et al., 2018).

2. Methodology

2.1 Preliminaries

Spherical fuzzy sets are used to represent the fuzziness and ambiguity in providing judgments in linguistic scale in AHP pairwise comparison and rating of alternatives via TOPSIS. This section introduces the definitions related to spherical fuzzy set and its generalization. Spherical fuzzy set was introduced independently in Mahmood et al. (2019), and in Gündoğdu and Kahraman (2019) to model the ambiguous human opinion as a generalization of Zadeh's fuzzy set and its extension such as that of intuitionistic fuzzy set and picture fuzzy sets. For example, Atanassov's intuitionistic fuzzy set (IFS) expressed the fuzziness of human opinion by adding the non-membership function to the ordinary fuzzy set and satisfies that the sum of the membership degree (μ) and non-membership degree (π) does not exceed one (i.e., $0 \leq Sum(\mu, \pi) \leq 1$). Pythagorean fuzzy sets or IFS2 strengthen the concept of IFS by enlarging the space of membership and non-membership with the condition that $0 \leq Sum(\mu^2, \nu^2) \leq 1$. However, there is decision making under uncertain environment which requires not only either a yes (membership degree) or no (non-membership degree) but also some degree of neutrality due to hesitation. Accordingly, Cuong (2014) extends IFS by introducing the neutrality or indeterminacy degree (π) under the condition that $0 \leq Sum(\mu, \pi, \pi) \leq 1$. Likewise, spherical fuzzy sets and its generalization, T-spherical fuzzy set enlarge the space for the three components (μ, π, π).

Definition 1. Let X be in a finite domain and $x \in X$. T-spherical fuzzy set (TSF) is defined as: $T = \{x, \mu(x), \nu(x), \pi(x) \mid x \in X\}$ with the condition that $0 \leq Sum(\mu^t, \nu^t, \pi^t) \leq 1, \forall\ t \in Z \geq 1$. Here the three components $\mu, \nu, \pi: X \rightarrow [0,1]$ represents the degree of membership, degree of non-membership, and degree of indeterminacy, respectively. Z refers to positive integers wherein a particular case of T in X, for example is a spherical fuzzy set (SFS) at $t = 2$ with the condition of $0 \leq Sum(\mu^2, \nu^2, \pi^2) \leq 1$, i.e., $0 \leq \mu^2 + \nu^2 + \pi^2 \leq 1$.
For ease of computation, a spherical fuzzy number is designated as an ordered triple: $\tilde{T}_s = (\mu_{\tilde{T}_s}, \nu_{\tilde{T}_s}, \pi_{\tilde{T}_s})$.
Definition 2. Let X be in a finite domain and $x \in X$. Spherical fuzzy number is defined as a single-valued spherical fuzzy set: $\tilde{S} = \{x, \mu_{\tilde{S}}, \nu_{\tilde{S}}, \pi_{\tilde{S}} \mid x \in X\}$ with the condition that $0 \leq Sum(\mu_{\tilde{S}}^2, \nu_{\tilde{S}}^2, \pi_{\tilde{S}}^2) \leq 1$.
SWAM, as defined in Eq(1), is an aggregation operator for *n* spherical fuzzy numbers $(\tilde{T}_{s1} \ldots\ldots \tilde{T}_{sn})$ in X using weighted arithmetic mean such that the weight vector $w_i \in [0,1]$; $\sum_{i=1}^{n} w_i = 1$ where $t = 2$.

$$SWAM(\tilde{T}_{s1} \ldots\ldots \tilde{T}_{sn}) = w_1\tilde{T}_{s1} + w_2\tilde{T}_{s2} + \cdots + w_n\tilde{T}_{sn} = \sum_{i=1}^{n} w_i\tilde{T}_{Si} = \left\{\left[1 - \prod_{i-1}^{n}\left(1 - \mu_{\tilde{T}_{si}}^t\right)^{w_i}\right]^{\frac{1}{t}}, \prod_{i=1}^{n} \nu_{\tilde{T}_{si}}^{w_i}, \left[\prod_{i-1}^{n}\left(1 - \mu_{\tilde{T}_{si}}^t\right)^{w_i} - \prod_{i=1}^{n}\left(1 - \mu_{\tilde{T}_{si}}^t - \pi_{\tilde{T}_{si}}^t\right)^{w_i}\right]^{\frac{1}{t}}\right\} \quad (1)$$

Definition 3. Defuzzification of spherical fuzzy number is defined in Eq(2) as follows:

$$Score(\tilde{T}) = 1 - \left[\frac{1}{3}\left\{(1 - \mu^t)^\beta + (\nu^t)^\beta + (\pi^t)^\beta\right\}\right]^{1/\beta} \quad (2)$$

where $\beta \geq 1$ is the distance parameter. Here the $Score(\tilde{T}) \rightarrow [0,1]$.

2.2 Proposed AHP-TOPSIS with Spherical Fuzzy Number

Step 1: Compute the criteria weights by SFAHP (Gündoğdu and Kahraman, 2019).
Value judgments are elicited via linguistic ratings to describe the relative importance of one criterion over the other to populate the fuzzy pairwise comparison matrix. The Spherical Fuzzy Number is used to describe the linguistic scale for the intensity of influence as described in Table 1 (Kuok and Promentilla, 2021).

Table 1: 9-point spherical fuzzy linguistic scale for AHP pairwise comparison

Linguistic term	Symbol	M	v	π	Score index (SI)
Very highly more important	VHI	0.900	0.100	0.100	8
Highly more important	HMI	0.800	0.200	0.250	5
Moderately more important	MMI	0.700	0.300	0.350	3
Slightly more important	SMI	0.600	0.400	0.400	2
Equally important	EI	0.500	0.400	0.400	1
Slightly less important	SLI	0.400	0.600	0.400	1/2
Moderately less important	MLI	0.300	0.700	0.350	1/3
Highly less important	HLI	0.200	0.800	0.250	1/5
Very highly less important	VLI	0.100	0.900	0.100	1/8

Note that a_{ij} describe the intensity of importance of criterion i over criterion j. Score indices (SI) in Eqs(4) and (5) are used as entries in the classical AHP matrix to determine the level of consistency of judgments from the respondents.

$$A = \begin{bmatrix} EI & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & EI \end{bmatrix} \tag{3}$$

for linguistic terms VHI, HMI, SMI, EI:

$$SI = \sqrt{\left|100 * \left[\left(\mu_\varphi - \pi_\varphi\right)^2 - \left(\nu_\varphi - \pi_\varphi\right)^2 \right]\right|} \tag{4}$$

for linguistic terms VLI, HLI, SLI, EI:

$$\frac{1}{SI} = \frac{1}{\sqrt{\left|100 * \left[\left(\mu_\varphi - \pi_\varphi\right)^2 - \left(\nu_\varphi - \pi_\varphi\right)^2 \right]\right|}} \tag{5}$$

The relative priorities of criteria is computed using the spherical weighted arithmetic mean described in Eq(1) to aggregate the row entries in the pairwise comparison matrix. The score function described in Eq(6) is used to compute the crisp criteria score, and them normalized using Eq(7).

$$\tilde{w}_i^s = \sqrt{100\left[\left(3\mu_{\tilde{W}_i} - \frac{\pi_{\tilde{W}_i}}{2}\right)^2 - \left(\frac{\nu_{\tilde{W}_i}}{2} - \pi_{\tilde{W}_i}\right)^2\right]} \tag{6}$$

$$\bar{w}_i = \frac{\tilde{w}_i^S}{sum(\tilde{w}_1^S, \tilde{w}_2^S, \dots \tilde{w}_n^S)} \tag{7}$$

Step 2: Rank the alternatives using TOPSIS approach
TOPSIS ranks the alternatives using the following five steps. First, populate the decision matrix of *m* alternatives by *n* criteria with performance scores. The scores could be quantitative or qualitative assessment. For qualitative assessment, the linguistic scale shown in Table 2 is used and Eq(2) is used to transform the linguistic rating to crisp scores. Note that the distance parameter is set to $\beta = 19/8$ to set the score of moderate/satisfactory rating to 0.50.

In the second step, the weighted normalized decision matrix is generated using the following equations:

$$\overline{X_{ij}} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}} \tag{8}$$

$$V_{ij} = \overline{X_{ij}} \times W_j \quad (9)$$

Table 2: Linguistic scale used for qualitative assessment

Linguistic rating	Symbol	μ	ν	π	Scores
Ideal Best/Perfect	IB	1	0	0	1.000
Excellent	EX	0.900	0.100	0.100	0.880
Very good	VG	0.800	0.200	0.250	0.771
Good	GD	0.700	0.300	0.350	0.672
Slightly good/Above satisfactory	AS	0.600	0.400	0.400	0.585
Moderate/Satisfactory	S	0.500	0.500	0.500	0.500
Slightly bad/Below Satisfactory	BS	0.400	0.600	0.400	0.438
Bad	BD	0.300	0.700	0.350	0.373
Very bad	VB	0.200	0.800	0.250	0.307
Worst	WO	0.100	0.900	0.100	0.236
Ideal Worst	IW	0	1	0	0.157

Step 3: In the third step, positive ideal and negative ideal solutions are identified depending on whether the criterion is a benefit or cost type. For example, if the criterion is a cost type, the lower the score, the better the performance of the alternative with respect to that criterion. Thus, the positive ideal is the lowest possible score among the alternatives and the negative ideal is the highest possible score among the alternative with respect to that cost criterion. Likewise, the positive ideal is the highest possible score among the alternatives and the negative ideal is the lowest possible score among the alternative with respect to that benefit criterion.

Step 4: A measure of the separation via Euclidian distance from the positive ideal and negative ideal solution is computed in the fourth step using the following equations:

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right]^{0.5} \quad (10)$$

$$S_i^- = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2\right]^{0.5} \quad (11)$$

Lastly, the relative closeness to the ideal solution is computed in Eq(12), which was used to rank the alternatives.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (12)$$

3. Results and Discussion

The decision matrix used for this case study is given in Table 3 with alternative insulation materials, A1, A2, A3, A4, A5, to be ranked using the multiple criteria, C1, C2, C3, C4. The criterion C2, the product of density x specific heat is also known as thermal capacitance and is a measure of thermal storage capacity. As shown in Table 4, the criteria C1, thermal conductivity, and C3, embodied carbon, are classified as Cost criteria, the lower the better; and C2, density x specific heat, and C4, fire rating, are classified as Benefit criteria, the higher the better.

Table 3: Characteristics prioritized for the insulation material alternatives

Alternative insulation Materials	Thermal Conductivity, k (W/m °C)	Product of Density x specific heat, cp x d (kJ/kg °C) x (kg/m^3)	Embodied carbon (kg CO_2/kg)	Fire Rating
A1, geopolymer (foamed, fly ash-based)	0.05223[a]	196.2[a]	0.12[b]	VG[c] = 0.771
A2, fiberglass	0.031[d]	54.4[d]	7.7[d]	AS[d] = 0.585
A3, rock wool	0.03[d]	130[d]	2.77[d]	VG[d] = 0.771
A4, expanded polystyrene	0.031[d]	37.5[d]	3.25[d]	AS[d] = 0.585
A5, sheep wool	0.033[d]	60[d]	0.2[d]	AS[d] = 0.585

Sources: (a) k and d from Shao et al. (2018), cp from Carabba (2018); (b) Kalaw et al. (2016); (c) Provis (2010); (d) Grazieschi et al. (2021). NOTES: VG = very good, AS = above satisfactory, see Table 2.

Table 4: Criteria for evaluation, type of criterion, and pairwise comparison of criteria (row vs column)

Criterion	Type	C1	C2	C3	C4
C1, thermal conductivity	Cost	EI	MMI	HMI	MMI
C2, density x sp heat	Benefit	MLI	EI	HMI	EI
C3, embodied carbon	Cost	HLI	HLI	EI	HLI
C4, fire rating	Benefit	MLI	EI	HMI	EI

Table 4 shows the sample pairwise comparison matrix used in SFAHP to determine the importance weights of the criteria. The entries reflect the subjective judgment describing the relative importance of one criterion over the other. For example, in row 1 and column 2, MMI means that C1 is considered to be moderately more important (MMI) than C2, in row 1 and column 3, HMI means that C1 is considered highly more important (HMI) than C3, and so on. These judgments are then represented by the spherical fuzzy number (see Table 1). Eq(1) is used to compute the spherical fuzzy weights of each criterion. The fuzzy weights are then defuzzified and normalized using Eq(6) and Eq(7) respectively to compute the priority weights ($\overline{wi}$). The values of ($\overline{wi}$), shown in Table 5, are then used to determine the weighted normalized decision matrix using Eq(8) and Eq(9) to obtain the values in Table 6.

Table 5: The alternatives vs criteria matrix with computed normalized weights

		Criteria			
Alternatives		C1	C2	C3	C4
	Criteria Type	Cost	Benefit	Cost	Benefit
	Weights, $\overline{w_i}$	0.327	0.270	0.134	0.270
A1		0.052	196.200	0.120	0.771
A2		0.031	54.400	7.700	0.585
A3		0.030	130.000	2.770	0.771
A4		0.031	37.500	3.250	0.585
A5		0.033	60.000	0.200	0.585

Table 6: Weighted normalized decision matrix

	C1	C2	C3	C4
A1	0.641	0.779	0.014	0.518
A2	0.380	0.216	0.873	0.393
A3	0.368	0.516	0.314	0.518
A4	0.380	0.149	0.368	0.393
A5	0.405	0.238	0.057	0.393

Using Eq(10) and Eq(11), the Euclidean distance from the ideal best, S_i^+, and from the ideal worst, S_i^- are computed, and then the performance score, P_i, was determined using Eq(12). The summary of results is shown in Table 7.

Table 7: Summary of results

	material	S_i^+	S_i^-	P_i	Rank
A1	geopolymer (foamed, fly ash-based)	0.089	0.208	0.700	1
A2	fiberglass	0.194	0.087	0.310	5
A3	rock wool	0.082	0.157	0.657	2
A4	expanded polystyrene	0.180	0.109	0.377	4
A5	sheep wool	0.150	0.140	0.481	3

The pairwise comparison as seen in Table 4 is based on conventional selection criteria that gives more priority to insulation properties and lesser emphasis on environmental concerns. Thus, from Table 5, it is seen from the computed weights that thermal conductivity (C1) is the highest priority in consideration, followed by product (C2) of density x specific heat (thermal capacitance), and fire rating (C4), while embodied carbon (C3), is the least. It is seen that the multi-criteria combination of material properties, C1, C2 and C4, and an environmental factor, C3, the performance scores calculated showed the alternative A1, geopolymer (foamed, fly ash-based) to be ranked number 1 among the selected alternative insulation materials. Ranked 2nd is rock wool, 3rd is sheep wool, 4th is expanded polystyrene and 5th is fiberglass.

4. Conclusions

In this case study of using spherical fuzzy analytic hierarchy process (SFAHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) for a multi-criteria comparison of conventional insulation materials with geopolymers (foamed, fly ash-based), the potential of foamed geopolymers as an alternative building insulation material is brought to light. Based on the criteria selected and the weighting provided, as an initial set for this case study, the geopolymer alternative is ranked best. Future work will consider sensitivity analysis as the ranking results may differ if the decision maker sets a different priority on the criteria. As this model considered only 4 criteria, the addition of other criteria such as economic and health factors may also tilt the weights and provide a different ranking. In any case, this case study may be used as a template for comparisons with other alternative materials and with other or additional criteria for decision-making.

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