Article

Model for the Sustainable Material Selection by Applying Integrated Dempster-Shafer Evidence Theory and Additive Ratio Assessment (ARAS) Method

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Abstract: The construction industry is a vital part of the modern economic system. Construction work often has significant negative impacts on the environment and sustainable economic development, such as degradation of the environment, depletion of resources, and waste generation. Therefore, environmental concerns must be taken into account when evaluating and making decisions in the construction industry. In this regard, sustainable construction is considered as the best way to avoid resource depletion and address environmental concerns. Selection of sustainable building materials is an important strategy in sustainable construction that plays an important role in the design and construction phase of buildings. The assessment of experts is one of the most important steps in the material selection process, and their subjective judgment can lead to unpredictable uncertainty. The existing methods cannot effectively demonstrate and address uncertainty. This paper proposes an integrated Dempster-Shafer (DS) theory of evidence and the ARAS method for selecting sustainable materials under uncertainty. The Dempster-Shafer Evidence Theory is a relatively new and appropriate tool for substantiating decisions when information is nonspecific, ambiguous, or conflicting. The Additive Ratio Assessment (ARAS) method has many advantages to deal with MCDM problems with non-commensurable and even conflicting criteria and to obtain the priority of alternatives based on the utility function. The proposed method converts experts' opinions into the basic probability assignments for real alternatives, which are suitable for DS evidence theory. It uses the ARAS method to obtain final estimation results. Finally, a real case study identifying the priority of using five possible alternative building materials demonstrates the usefulness of the proposed approach in addressing the challenges of sustainable construction. Four main criteria including economic, social, environmental, and technical criteria and 25 sub-criteria were considered for the selection of sustainable materials. The specific case study using the proposed method reveals that the weight of economic, socio-cultural, environmental, and technical criteria are equal to 0.327, 0.209, 0.241, and 0.221, respectively. Based on these results, economic and environmental criteria are determined as the most important criteria. The results of applying the proposed method reveal that aluminum siding with a final score of 0.538, clay brick with a score of 0.494, and stone façade with a final score of 0.482 are determined as the best alternatives in terms of sustainability.

Keywords: material selection; sustainability; Dempster-shafer evidence theory; MCDM; ARAS; BWM

1. Introduction

All operations related to the construction, operation, or demolition of a building affect the environment in various ways and can be considered as environmental factors [1,2]. Because of depleting resources and environmental concerns, researchers and practitioners

have begun to explore sustainable construction strategies. Human health and the environment will be at a disadvantage and greenhouse gases will destroy the ozone layer if the devastating effects of this part of the economic system are not considered. It is argued that the most critical factors in natural disasters are environmental issues and hazards [3,4]. Figure 1 presents the model for sustainable material selection.
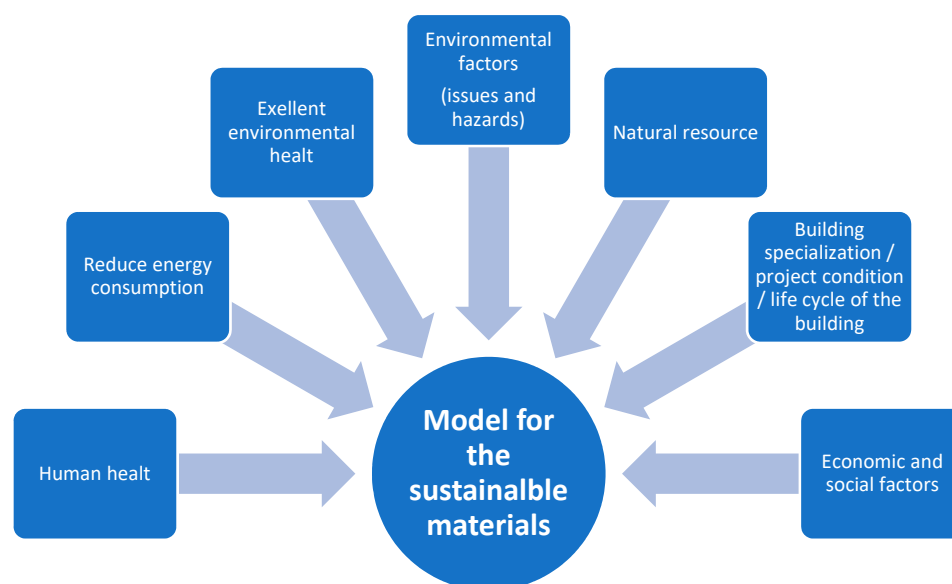
Figure 1. The model for sustainable material selection.

Advances in science and technology have changed the environment to meet the needs of human well-being [5]. The extraction of raw materials needed for construction, such as wood, sand, clay, and others, causes irreversible effects on the natural environment. A well-designed building made of sustainable materials is less harmful to the environment and improves the life cycle of the building. Such a building will also significantly reduce life cycle costs [6–8].

Three principles of development, considering building as a part of the environment including economic and social components [9,10], are the basis for defining sustainable construction of the human-built environment. Sustainable building addresses not only environmental sustainability but also economic and social sustainability. Moreover, the sustainable concept is closely related to both international and local perspectives [11]. The sustainable building benefits the economy by reducing operating costs, enhancing marketability, improving employee productivity and productivity, creating benefits for office buildings, minimizing adverse impacts and interiors, and enhancing the economic performance of the building life cycle [10,12,13]. Proper construction and environmental protection of materials used in buildings are essential. The choice of sustainable and suitable building materials will reduce energy consumption, provide better environmental health, reduce the use of natural resources [14–16], and reduce waste generation [17]. Using suitable materials is one way to achieve sustainable architecture and thus manage environmental hazards more efficacious [18,19]. Unfortunately, potential risk factors and a lack of accurate knowledge by stakeholders in a dynamic business environment expose construction projects [20].

Esin [21] classified the material selection factors into three groups: functional, financial, and maintenance. Functional requirements are essential for a proper comparison of the materials. Variants include functional and technical requirements that define measurable criteria such as hardness and stiffness.

Akadiri et al. [22] provided sustainable evaluation criteria for the selection of building materials. First, based on previous research results, the authors selected the criteria for

choosing materials. They determined the data to compare the choices according to the answers provided by experts.

Various methods are helpful for solving sustainable material selection problems. For instance, Mousavi-Nasab and Sotoudeh-Anvari [23] proposed a new multi-criteria decision-making (MCDM) way to select materials. The presented method generates more logical results than those obtained by three of the most popular techniques in the material selection area. Roy et al. [4] proposed an MCDM evaluation framework by extending the COmbinative Distance ASsessment (CODAS) method [24] with interval-valued intuitionistic fuzzy numbers. Mathiyazhagan et al. [8] applied a three-stage approach to select materials under a fuzzy environment. The authors selected 23 sub-criteria, employed the Best-Worst methodology (BWM) [25] to determine criteria and sub-criteria weights, and used fuzzy TOPSIS to evaluate materials.

Govindan et al. [26] proposed an integrated DEMATEL-ANP-TOPSIS [27–29] approach to select materials. The authors utilized DEMATEL to determine the interrelationship among evaluation criteria, employed ANP to determine the weights, and applied TOPSIS to evaluate the performance of available alternatives. Mahmoudkelaye et al. [30] presented other applications of the ANP methods for sustainable material selection.

Zavadskas et al. [31] presented a theoretical evaluation model based on the SWARA (Step-wise Weight Assessment Ratio Analysis) [32] approach and MULTIMOORA (multi-objective optimization by ratio analysis plus full multiplicative form) [33] method for residential house construction materials and elements selection. Chen et al. [34] proposed a multiple criteria group decision-making approach based on a quality function deployment (QFD) and ELECTRE III method for sustainable material selection. Reddy et al. [35] introduced a sustainable material performance index based on the social, environmental, economic, and technological criteria for selecting sustainable material in the construction industry.

Most authors use methods for assessing the sustainability of materials under certain conditions. Additionally, some of the authors used concepts and practices in their reports to cover data uncertainties related to the values of the evaluation criteria. This paper presents the Dempster-Shafer Evidence Theory-based selection model to substantiate uncertain information in expert conclusions on material evaluation criteria. Evidence theory is a new powerful tool for decision-making, handling uncertain information, and managing conflicting information. The purpose of this work is to provide a model for justifying effective choices based on Dempster-Shafer Evidence Theory and the ARAS method for evaluating materials based on sustainability characteristics. In addition, the authors use the ARAS method to assess and select sustainable options.

Zavadskas and Turskis developed the ARAS method in 2010 [36]. Table 1 presents a review of the ARAS method modifications and applications.

Table 1. The review of the ARAS method modifications and applications.

Year	ARAS	Extended ARAS Method	Applications for the Assessment	Literature Reference
2010	ARAS			[36]
		ARAS-F		[37]
		ARAS-G		[38]
	ARAS		Foundation Instalment	[39]
2011	ARAS		Pile-Columns	[40]
	ARAS	ARAS-F	Architect Selection	[41]
2012	ARAS		Experimental Study on Technological Indicators of Pile-Columns	[42]
	ARAS		Projects Managers	[43]
	ARAS		Lithuanian Economic Sectors	[44]
2013		ARAS-G	Prioritizing of Heritage Value	[45]
	ARAS		Preservation of Historic City Centre Buildings	[46]

Table 1. *Cont.*

Year	ARAS	Extended ARAS Method	Applications for the Assessment	Literature Reference
2014		ARAS-F	Selection of the Chief Accountant	[47]
		Fuzzy GARAS	Waste Dump Site Selection	[48]
		Fuzzy ARAS	Model for Extending Brand	[49]
		ARAS-F	Financial Performance Evaluation	[50]
2015	ARAS	ARAS-F	Deep-Water Port in the Eastern Baltic Sea	[51]
			Sustainable Building Assessment/Certification	[19]
		ARAS with interval-valued triangular fuzzy		[52]
		ARAS-F		[53]
2016	ARAS		Ranking of Companies	[54]
	ARAS		Biomass Selection	[55]
	ARAS		Personnel Selection	[10]
	ARAS		Model to Assess a Stairs Shape for Dwelling	[56]
		PMADM		[57]
		Fuzzy ARAS		[58]
	ARAS		Evaluation of Research and Technology Organizations Based on BSC Approach	[59]
2017	ARAS		Ranking of Energy Generation Scenarios	[60]
	ARAS		Complicated Supply Chain Management Problems	[61]
		ARAS-F	Personnel Assessment Problems	[62]
	ARAS		Negotiations	[63]
	ARAS		Cultural Heritage Structures for Renovation Projects	[64]
2018		ARAS-G	Personnel Selection	[65]
	ARAS		Evaluate Mobile Banking Services	[66]
	ARAS		Selection of Optimum Process Parameters in Turning Process	[67]
	ARAS		Machinery/Service System Scheduled Replacement Time Determination	[68]
	ARAS		Identification of Erosion-Prone Areas	[69]
		ARAS-F	Evaluation of Organizational Strategy Development	[70]
	ARAS		Selection of a Brake Disc Material	[71]
		rough ARAS	Measuring Performance in Transportation Companies	[72]
	ARAS		Determining the Utility in Management	[73]

Table 1. *Cont.*

Year	ARAS	Extended ARAS Method	Applications for the Assessment	Literature Reference
2019		NARAS	Selection of Material for Optimal Design of Engineering Components	[74]
	ARAS		Information System Fault-Tolerance	[75]
		Fuzzy ARAS	Determination of Individuals' Life Satisfaction Levels Living	[76]
		AHP-ARAS	EDM Process Parameters on Machining AA7050-10%B4C Composite	[77]
		ARAS-F	Supplier Selection	[78]
		IVIF-ARAS	Smartphone Selection Problem	[79]
		ARAS-G	Construction Delay Change Response Problem	[80]
		ARAS-F	Assessment of Structural Solutions of the Symmetric Frame Alternatives	[81]
	ARAS		Catering Supplier Selection	[82]
	ARAS		Sustainable Supplier Selection in a Construction Company	[83]
		ARAS-IT2HFSs	Underground Site Selection:	[84]
		fuzzy ARAS	Personnel Selection Problem	[85]
		FCM-ARAS	Financial Performance	[86]
	ARAS		Selecting a Suitable Maintenance Strategy for Public Buildings using Sustainability Criteria	[87]
		Entropy-ARAS	Assessing Corporate Sustainability Performances of Privately-owned Banks	[88]
	ARAS		Evaluating Autonomous Vehicles	[89]
		BWM-ARAS	Prospectivity Mapping	[90]
		fuzzy ARAS	Supplier Selection Problem	[91]
2020	ARAS		Analysis of Companies' Digital Maturity	[92]
	ARAS		Location Selection for Logistics Center	[93]
	ARAS		Location Preferences of new Pedestrian Bridges	[94]
		hybrid SWARA-ARAS	Sustainability Indicators for Renewable Energy Systems	[95]
		HFLTS- ARAS	Selection of Eco-friendly Cities	[96]
		F-ARAS	Prioritizing the Outsourcing Performance Outcomes	[97]
		IF-ARAS	Personnel Selection	[98]
		PIPRECIA-Interval-Valued Triangular Fuzzy ARAS	E-Learning Course Selection	[99]

The rest of this article is organized as follows. Section 2 presents the aim and objectives of the paper. Section 3 describes the Dempster-Shafer Evidence Theory and the ARAS method. Next, Section 4 presents the proposed integration of the Dempster-Shafer Evidence Theory and the ARAS method. Section 5 shows the use of the presented methodology to evaluate five sustainable materials for the building facade. The last section gives concluding remarks.

2. Aim and Objectives

The choice of sustainable materials can be considered as an MCDM problem in which a set of alternatives should be evaluated based on several sustainability criteria. These criteria, alternatives, and tier-respected information form the decision matrix in the MCDM problem. In this paper, the ARAS method is used to evaluate and prioritize alternatives. In reality, it is very difficult to determine the value of the criteria accurately, and in many cases the information that can be collected is uncertain. Therefore, to model the MCDM problem for sustainable material selection, a case study has been conducted in this paper that focuses on information that has uncertainty and can be expressed in terms of the basic probability assignments in the evidence theory. Accordingly, each of the matrix elements of the decision matrix is expressed as a basic probability assignment. The rule of composition is used to prepare the final decision matrix, and the elements of the decision matrices of all experts are fused to obtain the final decision matrix. This matrix is later used in the ARAS method. In addition, to determine the importance of the criteria, a weighting method based on evidence theory is utilized in this paper, and based on it, the decision matrix used in the ARAS method is weighted.

This paper aims to introduce an evidential model based on DS evidence theory and the ARAS method to solve the problem of sustainable material selection under uncertainty. The primary objectives of this paper are summarized below:

- Objective 1: Introducing a practical way to extract the basic probability assignments from the evaluation of information of experts by expressing linguistic terms and confidence levels. This is an effective way to deal with uncertain information in MCDM problems in which decision-makers can consider the evaluation itself without formality and can also employ imperfect or insufficient knowledge of data.
- Objective 2: Obtaining the final decision matrix in terms of the basic probability assignments. The final decision matrix is obtained based on fusion results and is employed later in the ARAS method.
- Objective 3: Applying a weighting method based on the Deng entropy for determining the weights of sustainability criteria. These weights will be employed to obtain the weighted decision matrix.
- Objective 4: Applying the ARAS method on the decision matrix to obtain the ranking results and prioritize alternatives (sustainable materials).

3. Preliminaries

3.1. Dempster–Shafer Theory of Evidence

Dempster-Shafer's theory of evidence is a valuable tool to cope with the substantial uncertainty in the experts' opinions. Dempster in 1967 introduced this theory, and then Shafer in 1976 [100,101] expanded it. This theory is a powerful way to combine evidence extracted from different sources. The belief functions used in Dempster-Shafer's theory of evidence, compared to probability theory, provide more information to support decision-making by unknown and uncertain evidence and a mechanism for deriving solutions to ambiguous and different evidence without prior information and possibilities. This theory has successful applications in many fields, including knowledge reduction [102], error detection [103], multi-class classification [104], supplier selection [105], and others.

3.1.1. Mass Function

In the Dempster–Shafer Evidence Theory, also referred to as the DS Theory of Evidence, a set of elementary hypotheses such as $H_1, H_2, \ldots, H_n$ define the frame of discernment as follows [106]:

$$\theta = \{H_1, H_2, \ldots, H_n\} \tag{1}$$

where θ denotes a set of mutually exclusive and collectively exhaustive events. A nomenclature table is added in Appendix A to define the variables and notations used in the paper.

The power set of θ is denoted by 2^θ. The mass function, which is called a basic probability assignment (BPA), is a mapping from the power set to the interval [0, 1] as follows [107]:

$$m : 2^\theta \to [0, 1]. \tag{2}$$

The mass function satisfies the following properties:

$$\begin{aligned} m(\theta) &= 0 \\ \sum_{A \in 2^\theta} m(A) &= 1 \end{aligned} \tag{3}$$

where A is a member of the power set. If $m(A) > 0$, then A is called a focal element of the mass function.

3.1.2. Deng Entropy and the Weight of BPAs

Deng [107] introduced the new entropy measure called Deng entropy to measure the uncertainty degree of BPAs. Deng entropy is an extended form of Shannon entropy and is denoted by $E(BPA)$. Deng entropy is obtained as follows:

$$E(BPA) = -\sum_i m(F_i) \log \frac{m(F_i)}{2^{|F_i|} - 1}. \tag{4}$$

where $E(BPA)$ denotes Deng entropy, F_i is a proposition in mass function m, $m(F_i)$ denotes the mass function of F_i, and $|F_i|$ denotes the number of elements of F_i. The following equation calculates the maximum value of Deng entropy ($E_{\max}$):

$$E_{\max} = -\sum_i m(F_i) \log \frac{m(F_i)}{2^{|F_i|} - 1} \tag{5}$$

If and only if

$$m(F_i) = \frac{2^{|F_i|} - 1}{\sum_i 2^{|F_i|} - 1} \tag{6}$$

Considering the quality of information and the existing uncertainty in experts' judgments is very important before combining evidence. Fei et al. [106] reflected this matter by calculating the weight of the BPAs and modifying BPAs based on their weights before combining them. According to Fei et al. [106], the weight of a given BPA can be determined as follows:

$$w(BPA) = 1 - \frac{E(BPA)}{E_{\max}} \tag{7}$$

where $w(BPA)$ denotes the weight of a given BPA, $E(BPA)$ is the Deng entropy for a given BPA, and $E_{\max}$ is the maximum value of Deng entropy

3.1.3. Discounted BPA

The basic probability assignment can be modified by a discounting coefficient denoted by α. When the evidence is believed by probability α, the discounted BPA is obtained by the following equations:

$$\begin{aligned} m^\alpha(A) &= \alpha \times m(A) \quad A \in \theta \\ m^\alpha(\theta) &= (1 - \alpha) \times m(\theta) \end{aligned} \tag{8}$$

where A is the focal element of the mass function m [106]. The weight of BPA can be considered as the discounting coefficient to reduce the uncertainty degree in the evidence.

3.1.4. Dempster's Rule of Combination

To combine two BPAs m_1 and m_2, Dempster's rule of combination is used. The combined evidence is denoted by $m = m_1 \oplus m_2$ and calculated as follows:

$$m(A) = \frac{1}{1-k} \sum_{B \cap C = A} m_1(B) \, m_2(C),$$
$$k = \sum_{B \cap C = \theta} m_1(B) \, m_2(C) \qquad (9)$$

where k states the conflict between two BPAs m_1 and m_2, and $m(A)$ shows the combined BPA.

If there are more than two BPAs for combinations, the extended Dempster's rule of combination is applied as follows:

$$m = m_1 \oplus m_2 \oplus \cdots \oplus m_L = ((((m_1 \oplus m_2) \oplus m_3) \oplus \cdots) \oplus m_L) \qquad (10)$$

3.1.5. Pignistic Probability Transformation

A probability that a rational person will assign to an option when required to decide is a pignistic probability. Let m be a BPA on the frame of discernment θ. The following equation obtains the pignistic probability transformation for a given singleton $x \in \theta$. The goal of pignistic probability transformation is to convert a BPA to a probability distribution for decision making.

$$BetP\{x\} = \sum_{x \in A \subset \theta} \frac{1}{|A|} \frac{m(A)}{1 - m(\theta)}, \quad m(\theta) \neq 1. \qquad (11)$$

where $|A|$ denotes the cardinality of proposition A, and $BetP\{x\}$ shows the pignistic probability transformation for $x \in \theta$.

3.2. Additive Ratio Assessment (ARAS) Method

ARAS is a relatively new technique in multi-attribute decision making that has attracted researchers in recent years. Zavadskas and Turskis [36] introduced this technique in 2010. In this method, alternatives are ranked based on the optimality criterion. The steps of implementing the ARAS method are as follows [36]:

Step 1: In the first step, the decision-making matrix is formed. The dimension of this matrix is $m \times n$, where m denotes the number of alternatives (rows) and n shows the number of criteria (columns).

$$X = \begin{bmatrix} x_{01} & \cdots & x_{0j} & \cdots & x_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix}, \quad i = 0, 1, \ldots, m, \; j = 1, 2, \ldots, n \qquad (12)$$

where X denotes the decision-making matrix, x_{ij} denotes the rating of alternative i for criterion j, and x_{0j} presents the optimal value of j th criterion. If x_{0j} is unknown, then it is obtained by the following equations for the benefit and cost type criteria:

$$x_{0j} = \underset{i}{\text{Max}} \, x_{ij} \text{ if } \underset{i}{\text{Max}} \, x_{ij}, \text{ is preferable}$$
$$x_{0j} = \underset{i}{\text{Min}} \, x_{ij} \text{ if } \underset{i}{\text{Min}} \, x_{ij}, \text{ is preferable} \qquad (13)$$

where x_{0j} denotes the optimal value of j th criterion. Typically, optimal values are values that cannot be better in any way. Equation (13) is valid when stakeholders consider all possible alternatives, and there is no suitable alternative. This condition ensures that even if an option to include in or to remove it from the list of options in the research

case, the options' performance remains the same, and the performance level of considered alternatives is the same. This method ensures that the technique is resistant to changes in ratings (rank reversals). For example, if decision-makers are looking for options with a maximum return of 1, the expected optimal value is 1.2. For cost type criteria, this value is 0.8 if the least value is 1. When linguistic terms express the level of performance, then the maximum available linguistic value describes the optimal variant ($x_{0j} = 5$). Additionally, the decision-maker is real (equal to 1 in the case study).

Step 2: In the second step, the normalized decision-making matrix ($\overline{X}$) whose elements are denoted by $\overline{x}_{ij}$ is obtained. The dimension of this matrix is $m \times n$.

$$\overline{X} = \begin{bmatrix} \overline{x}_{01} & \cdots & \overline{x}_{0j} & \cdots & \overline{x}_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \overline{x}_{i1} & \cdots & \overline{x}_{ij} & \cdots & \overline{x}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \overline{x}_{m1} & \cdots & \overline{x}_{mj} & \cdots & \overline{x}_{mn} \end{bmatrix}, \quad i = 0, 1,, \ldots, m, \, j = 1, 2, \ldots, n \quad (14)$$

where $\overline{X}$ denotes the normalized decision-making matrix. The following formula normalizes the benefit type criteria:

$$\overline{x}_{ij} = \frac{x_{ij}}{\sum\limits_{i=0}^{m} x_{ij}} \quad (15)$$

Furthermore, the following formulas normalize the cost type criteria:

$$x_{ij} = \frac{1}{x_{ij}^*}, \quad \overline{x}_{ij} = \frac{x_{ij}}{\sum\limits_{i=0}^{m} x_{ij}} \quad (16)$$

Step 3: In this step, the normalized-weighted decision-making matrix ($\hat{X}$) is provided. Let w_j be the weight of j th criterion and the weights of criteria satisfy the equation $\sum\limits_{j=1}^{n} w_j = 1$. Deng entropy can be employed to obtain the weight of criteria. According to the [42], the weight of the j criterion can be formulated as follows:

$$w_j = \frac{D_j}{\sum_{j=1}^{n} D_j}, \quad (17)$$

where w_j is the weight of the j criterion and D_j denotes the consistency of alternatives for j criterion and calculated as:

$$D_j = 1 - E_j, \quad (18)$$

where E_j denotes the entropy of j criterion, which is calculated based on the Deng entropy according to the following equation.

$$E_j = -\sum_i m_j(F_i) \log \frac{m_j(F_i)}{2^{|F_i|} - 1} \quad (19)$$

The elements of the normalized-weighted decision-making matrix ($\hat{X}$) are denoted by $\hat{x}_{ij}$ and calculated as follows:

$$\hat{X} = \begin{bmatrix} \hat{x}_{01} & \cdots & \hat{x}_{0j} & \cdots & \hat{x}_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \hat{x}_{i1} & \cdots & \hat{x}_{ij} & \cdots & \hat{x}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \hat{x}_{m1} & \cdots & \hat{x}_{mj} & \cdots & \hat{x}_{mn} \end{bmatrix}, \quad i = 0, 1,, \ldots, m, \, j = 1, 2, \ldots, n \quad (20)$$

$$\hat{x}_{ij} = w_j \, \overline{x}_{ij}, \quad i = 0, 1, \ldots, m \tag{21}$$

Step 4: In this step, the optimality function and the utility degree of alternatives are calculated. The optimality function for alternative *i* is formulated as:

$$S_i = \sum_{j=1}^{n} \hat{x}_{ij}, \quad i = 0, 1, \ldots, m \tag{22}$$

where S_i denotes the optimality function of alternative *i*. The most significant value of S_i is the best, and the least one is the worst. The higher the value of S_i for *i* th alternative, the more useful alternative. The alternative utility K_i is determined by comparing the utility degree of alternative *i* with the ideally best one S_0. Alternatives can be prioritized based on their utility degree. The alternative utility can be written as follows:

$$K_i = \frac{S_i}{S_0}, \quad i = 0, 1, \ldots, m \tag{23}$$

where K_i denotes the alternative utility, which can take a value in the interval [0, 1]. The larger the value of K_i, the preferable alternative.

4. The Proposed DS Evidence Theory and the ARAS Method

This section presents the proposed DS evidence theory and the ARAS method for the sustainable material selection problem. The assessment of experts is one of the most important steps in the material selection process. The subjective judgment of experts may lead to unpredictable uncertainty. The existing approaches such as fuzzy set theory and the Bayesian method cannot effectively handle uncertainty. Fuzzy set theory is an effective tool to handle epistemic uncertainty, which comes from the lack of information. However, it cannot effectively reflect the conflicting information extracted from multiple sources. The DS method is an efficient tool to support decisions when information is nonspecific, ambiguous, or conflicting. The DS method is an extended form of the Bayesian method that has all its advantages. For example, in the DS method, as in the Bayesian method, existing prior information can be incorporated into the inference of uncertain indices and inferential results. However, the use of prior information in the DS method is not mandatory. This is one of the advantages of the DS method. Second, the DS method, unlike other possible methods such as the Bayesian method, does not require a previous probability calculation. Third, it has a flexible and understandable mass function. Fourth, providing the mass function is easy and convenient. Fifth, the computational complexity of this method is much less than the Bayesian method. All aforementioned discussions show the reasons for choosing the DS theory of evidence for handling uncertainty. The ARAS method has many advantages to deal with MCDM problems with non-commensurable and even conflicting criteria. In the ARAS method, the priorities of alternatives are determined based on the utility function value. Furthermore, the ratio with an optimal alternative is used when seeking to rank alternatives and find ways of improving alternatives. This paper proposed an integrated DS evidence theory and the ARAS method to solve the sustainable material selection problem, which uses the features of both evidence theory and the ARAS method.

How to select the best material can be stated as a multi-criteria decision-making problem. According to the multi-criteria decision-making problem, there are *m* alternatives $(A_1, A_2, \ldots, A_m)$, which must be evaluated by *n* criteria $(C_1, C_2, \ldots, C_n)$. Furthermore, let x_{ij} denotes the rating of alternative *i* for criterion *j*. The proposed method for sustainable material selection is depicted in Figure 2. As it can be seen in this Figure, the proposed method has four main parts including determine linguistic terms, construct BPAs, obtain a decision matrix, and prioritize alternatives. The proposed method includes several steps, as follows:
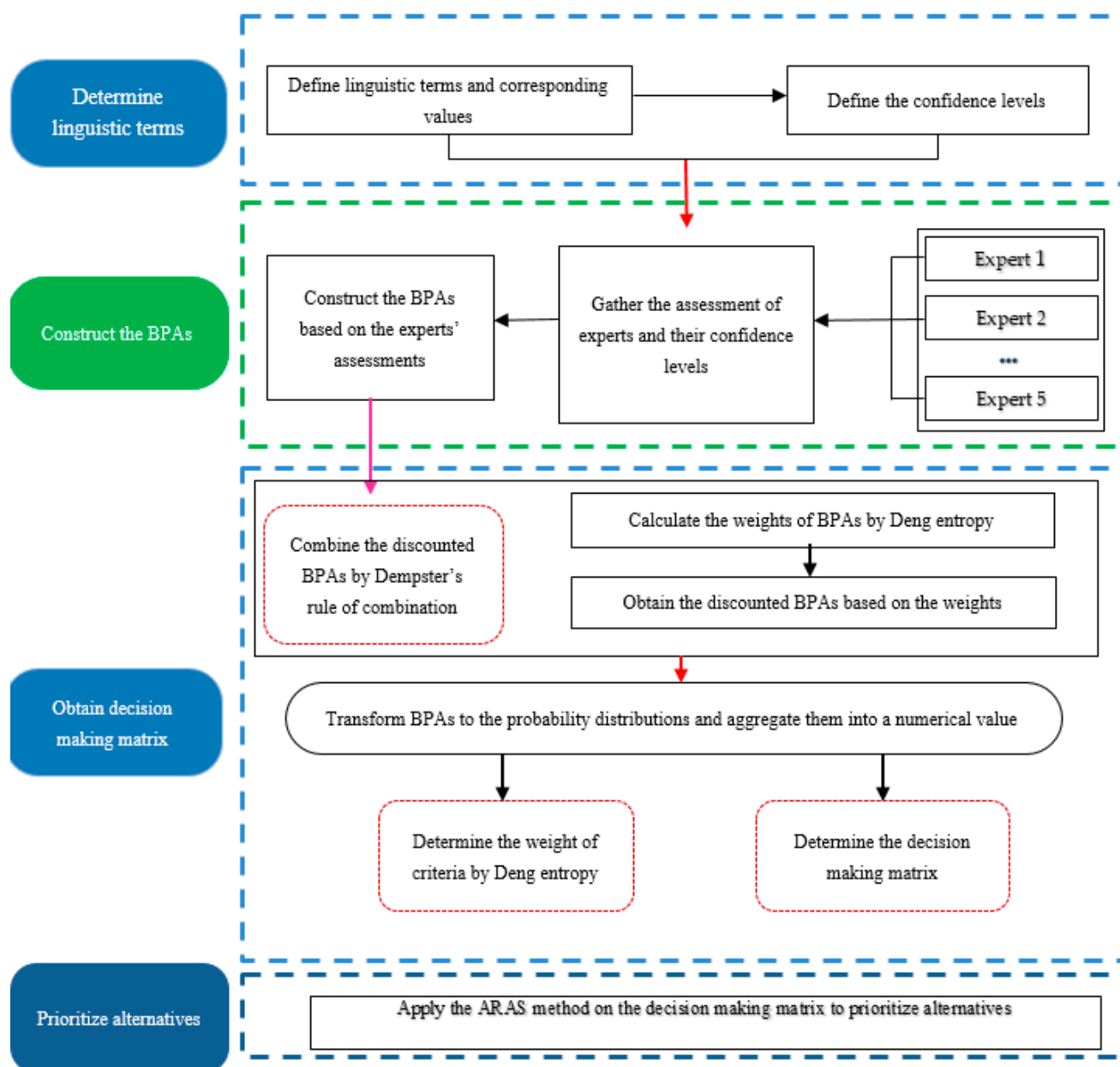
Figure 2. The flow chart of the proposed DS evidence theory and ARAS method.

Step 1: Define linguistic terms, corresponding values, and confidence levels

In multi-criteria decision-making problems, the ratings of alternatives for evaluation criteria must be determined. For doing so, the linguistic terms presented in Table 2 are used to evaluate alternatives concerning the evaluation criteria. Furthermore, Table 3 is used to help experts to assign confidence levels to their opinions about evaluation criteria. For instance, if an expert selects very low importance with a confidence level of 0.6, the expert is adequately convinced that the importance level is very low.

Table 2. Linguistic terms and their corresponding value [106].

Importance	Abbreviation	Linguistic Judgment	Corresponding Values
Very low	VL	Almost no recognition of the performance	1
Low	L	Low evaluation of the performance	2
Medium	M	The level of the performance is medium	3
High	H	High evaluation of the performance	4
Very high	VH	Almost fully recognized this performance	5

Table 3. The confidence levels [106].

Confidence Level	Scale
Fully convinced	1
Almost convinced	0.8
Properly convinced	0.6
Some convinced	0.4
Almost not convinced	0.2
Completely not convinced	0
Some intermediate values between two adjacent levels	0.9, 0.7, 0.5, 0.3, 0.1

Step 2: Convert experts' assessments to BPAs

In this step, the experts' judgments and their confidence levels are used to determine the BPAs. There are five elements in linguistic terms shown in Table 1 for rating alternatives. These elements are considered as the frame of discernment, and experts' assessment levels are considered the focal elements. Furthermore, the confidence levels determined by experts about their assessments can be seen as beliefs. Suppose that x_{ij} denotes the rating of alternative i for criterion j and the respected evaluation levels in x_{ij} are $A, B, \ldots$, and the corresponding confidence levels are $a, b, \ldots$. The BPA for this judgment can be written as follows:

$$m(A) = a$$
$$m(B) = b$$
$$\vdots$$
$$m(\theta) = 1 - a - b$$

For example, if an expert selects very low and low assessment levels with confidence levels 0.6, 0.1, respectively, the respected BPA can be denoted as: $m(VL) = 0.6$, $m(L) = 0.1$, $m(\theta) = 0.3$.

Step 3: Obtain the discounted BPAs

In this step, the discounted BPA is obtained for BPAs based on the weights of that BPA. For doing so, Deng entropy is first calculated based on Equation (4) to determine the entropy measure for a given BPA. Then, the weight of that BPA is calculated according to Equations (5)–(7). Finally, the discounted BPA is obtained by applying Equation (8).

Step 4: Combine the discounted BPAs

In this step, after obtaining the discounted BPAs associated with x_{ij} for each expert, they are combined by Dempster's rule presented in Equations (9) and (10).

Step 5: Apply the pignistic probability transformation

As the combined results for discounted BPAs are in the form of focal elements with mass function values, the pignistic probability transformation is used to convert them into a singleton element concerning linguistic terms of criteria. In this step, the pignistic probability transformation for each linguistic term of criteria is provided based on the

Equation (11). To obtain a numerical value for each criterion, the probability distribution must be integrated. For doing so, suppose that we have n linguistic terms with ratings $L_1, L_2, \ldots, L_n$ for evaluating a criterion. Furthermore, let $P_1, P_2, \ldots, P_n$ be the probability distribution concerning n linguistic terms. Then, the aggregated value, which is the mathematical expectation value of the criterion, is calculated as:

$$Aggregated\ value = L_1P_1 + L_2P_2 + \ldots + L_nP_n \qquad (24)$$

Step 6: Apply the ARAS method to prioritize alternatives

By applying step 5, the decision-making matrix is constructed. After that, the ARAS method formulated in Equations (12)–(20) is applied to the decision-making matrix to calculate alternative utility. Finally, alternatives are prioritized according to alternative utility (K_i).

5. Application of the Proposed Method for Sustainable Material Selection

In this section, the proposed method assesses the exterior enclosure materials based on the sustainability indicators. The exterior enclosure materials cover the buildings, protect them against undesirable climatic conditions, and maintain the optimum internal temperature. In this study, alternatives are considered as five materials used in the exterior of the building. They are aluminum siding (A_1), clay brick (A_2), glass facade (A_3), brick and mortar wall (A_4), and stone facade (A_5). These alternatives must be assessed based on sustainable criteria. The sustainable criteria for the construction material selection problem are extracted from the literature review. They are categorized into four groups: economic, environmental, socio-cultural, and technical criteria, and presented in Table 4.

Table 4. Sustainable material selection criteria [30,108].

Criteria	Sub-Criteria	Notation
Economic criterion (C_1)	Design and construction time	C_{11}
	Operational cost	C_{12}
	Cost of maintenance/repairs/service	C_{13}
	The durability of the building	C_{14}
	Market sentiment/public acceptance	C_{15}
	Return to baseline	C_{16}
	Transportation cost	C_{17}
Socio-cultural criterion (C_2)	The comfort of the occupants	C_{21}
	Impact on the local economy	C_{22}
	Workforce safety and health	C_{23}
	Preservation of cultural heritage	C_{24}
	Customer acceptance and satisfaction	C_{25}
	Skilled workforce availability	C_{26}
Environmental criterion (C_3)	Use of renewable materials and energy	C_{31}
	Water and Wastewater Productivity Strategies	C_{32}
	Regional materials	C_{33}
	Waste Management	C_{34}
	Greenhouse Gases	C_{35}
	Choosing the pitch	C_{36}
Technical criterion (C_4)	Weight of material	C_{41}
	Chemical resistance	C_{42}
	Water resistance	C_{43}
	Fire safety	C_{44}
	Structural capacity	C_{45}
	Useful life	C_{46}

The data must be gathered based on the experts' opinions. For this purpose, five architects with more than ten years of experience in designing and construction were

considered. According to step 1 of the proposed method, a questionnaire was used to ask about the status of criteria in each alternative. According to step 2 of the proposed method, the experts' opinions must be converted to BPAs. For example, according to the first expert opinion, the rating of alternative A_1 in terms of sub-criterion C_{11} is {H, VH} with a confidence level of 0.65. The respected BPA for this assessment is $m(\{H, VH\}) = 0.65$, $m(\theta) = 0.35$ (Objective 1). These steps of the proposed method and their explanations refer to objective 1 of the paper.

In step 3 of the proposed method, the discounted BPAs must be obtained. First, Deng entropy is calculated for each BPA according to Equation (4). Then, Equations (5)–(8) are used to calculate the weight of BPA and the discounted BPA, respectively. The maximum Deng entropy is calculated by Equations (5) and (6), and its value becomes 7.72. For the aforementioned BPA in the previous example, Deng's entropy value and the respected weight are calculated as 3.70 and 0.52, respectively. According to these results and Equation (8), the discounted BPA can be written as $m(\{H, VH\}) = 0.34$, $m(\theta) = 0.66$.

Similarly, the discounted BPAs are provided for all experts' evaluations. After that, according to step 4 of the proposed method, Dempster's rule of combination is utilized to combine the discounted BPAs extracted from experts' evaluations. Table 5 reports the combined results. In other words, Table 5 shows the decision matrix obtained from the aggregation of expert opinions. The decision matrix is reported in terms of BPAs in Table 5, which addresses objective 2 of the paper, which is shown in Table 5. In step 5 of the proposed method, the combined discounted BPAs are used to obtain the pignistic probability transformation for each linguistic term. Then, they are aggregated by Equation (24). Table 6 reports Betp and aggregated values for each alternative under different criteria.

Table 5. The combined discounted BPAs extracted from experts' evaluations.

Criteria	Alternatives	Combined BPA
C_{11}	A_1	m({VH}) = 1, m(θ) = 0
	A_2	m({M}) = 0.56, m({H,VH}) = 0.16, m(θ) = 0.28
	A_3	m({M,L}) = 0.12, m({M}) = 0.14, m({H}) = 0.32, m(θ) = 0.42
	A_4	m({VL}) = 0.03, m({M}) = 0.09, m({H}) = 0.53, m(θ) = 0.35
	A_5	m({M}) = 0.08, m({H}) = 0.2, m({VH}) = 0.41, m(θ) = 0.31
C_{22}	A_1	m({VH}) = 1, m(θ] = 0
	A_2	m({H}) = 0.1, m({VH}) = 0.72, m(θ) = 0.18
	A_3	m({M}) = 0.58, m({H}) = 0.16, m(θ) = 0.26
	A_4	m({VL}) = 0.04, m({L}) = 0.03, m({M}) = 0.59, m(θ) = 0.34
	A_5	m({L}) = 0.02, m({M}) = 0.11, m({H,VH}) = 0.49, m(θ) = 0.38
⋮		
C_{46}	A_1	m({VH}) = 1, m(θ) = 0
	A_2	m({M}) = 0.11, m({M,H] = 0.05, m({VH) = 0.48, m(θ) = 0.36
	A_3	m({M,H}) = 1, m(θ) = 0
	A_4	m({VL}) = 0.003, m({H}) = 0.68, m({H,VH}) = 0.2, m(θ) = 0.117
	A_5	m({L}) = 0.01, m({M}) = 0.19, m({VH}) = 0.44, m(θ) = 0.36

Table 6. Betp and aggregated values for each alternative under different criteria.

Criteria	Alternatives	Betp					Aggregated Values
		({VL})	({L})	({M})	({H})	({VH})	
C_{11}	A_1	0	0	0	0	1	5
	A_2	0.056	0.056	0.616	0.136	0.136	3.24
	A_3	0.084	0.144	0.284	0.404	0.084	3.26
	A_4	0.1	0.07	0.16	0.6	0.07	3.47
	A_5	0.062	0.062	0.142	0.262	0.472	4.02

Table 6. *Cont.*

Criteria	Alternatives	Betp					Aggregated Values
		({VL})	({L})	({M})	({H})	({VH})	
C_{12}	A_1	0	0	0	0	1	5.00
	A_2	0.036	0.036	0.036	0.136	0.756	4.54
	A_3	0.052	0.052	0.342	0.212	0.052	2.29
	A_4	0.108	0.098	0.658	0.068	0.068	2.89
	A_5	0.072	0.092	0.072	0.212	0.552	4.08
				$\vdots$			
C_{45}	A_1	0.158	0.158	0.263	0.263	0.158	3.10
	A_2	0.062	0.082	0.132	0.062	0.662	4.18
	A_3	0.044	0.044	0.044	0.574	0.294	4.03
	A_4	0.051	0.051	0.046	0.426	0.426	4.12
	A_5	0.064	0.334	0.064	0.064	0.474	3.55
C_{46}	A_1	0	0	0	0	1	5.00
	A_2	0.072	0.072	0.207	0.097	0.552	3.98
	A_3	0	0	0.500	0.500	0	3.500
	A_4	0.025	0.022	0.022	0.802	0.022	3.45
	A_5	0.072	0.082	0.262	0.072	0.512	3.87

The aggregated results reported in Table 6 form the decision-making matrix, which is presented in Table 7. In the last step of the proposed model, the ARAS method is applied to the decision-making matrix to obtain the alternative utility (K_i). The ARAS method presented in Equations (12)–(20) is employed.

Table 7. Decision-making matrix.

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{21}	C_{22}	C_{23}
A_1	5	5	3.552	5	5	1.840	2.236	5	1.992	3.600
A_2	3.072	4.324	2.484	2.876	3.620	3.780	3.168	3.148	2.334	4.005
A_3	2.756	1.874	5	1.790	2.345	1.556	1.752	1.752	2.208	1.690
A_4	2.980	2.278	2.776	2.577	4.250	3.310	2.458	3.435	3.710	2.726
A_5	3.834	3.792	3.792	3.834	3.038	2.985	3.834	3.834	3.656	2.630

	C_{24}	C_{25}	C_{26}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{41}
A_1	5	3.828	2.787	5	1.848	1.632	2.258	2.862	2.89	3.843
A_2	2.566	3.498	3.422	0.559	3.498	2.820	2.010	2.952	2.576	3.217
A_3	2.248	1.740	1.230	3.562	1.455	2.118	1.803	1.563	3.784	2.345
A_4	1	1.990	2.970	2.955	0.240	0.216	2.956	3.395	4.139	5
A_5	3.384	2.430	2.430	1.944	2.664	2.664	2.208	3.036	3.766	5

	C_{42}	C_{43}	C_{44}	C_{45}	C_{46}
A_1	2.756	3.116	3.240	3.895	5
A_2	3.594	3.948	3.870	3.870	3.769
A_3	2.348	2.5	3.038	3.766	3.500
A_4	3.425	3.843	3.696	3.987	3.233
A_5	2.756	3.116	3.240	3.895	5

After obtaining the decision-making matrix, it is normalized according to Equations (15) and (16). To calculate the weight of criteria, the combined discounted BPAs reported in Table 5 are used again to combine different BPAs of alternatives under the same criterion. Then, Equations (17)–(19) are utilized to calculate the weight of criteria. Table 8 reports the combined BPAs of alternatives under the same criterion and the weight of sub-criteria. Table 8 addresses objective 3 of the paper.

Table 8. Combined BPAs and weights for each sub-criterion.

Criteria	Combined BPA	E_j	D_j	w_j
C_{11}	m({VH}) = 1, m(θ) = 0	0	1	0.055
C_{12}	m({VH}) = 1, m(θ) = 0	0	1	0.055
C_{13}	m({VH}) = 1, m(θ) = 0	0	1	0.055
C_{14}	m({VH}) = 1, m(θ) = 0	0	1	0.055
C_{15}	m({VH}) = 1, m(θ) = 0	0	1	0.055
C_{16}	m({L] = 0.006, m({M,L}) = 0.001, m({M}) = 0.16, m({M,H}) = 0.16, m({H}) = 0.01, m({VH}) = 0.33, m(θ) = 0.33	3.93	0.49	0.027
C_{17}	m({L}) = 0.0005, m({M}) = 0.21, m({L,H}) = 0.004, m({H}) = 0.22, m({VH}) = 0.004, m(θ) = 0.56	4.27	0.45	0.025
C_{21}	m({VH}) = 1, m(θ) = 0	0	1	0.055
C_{22}	m({VL,L}) = 0.0007, m({L}) = 0.0002, m({M,L}) = 0.001, m({M}) = 0.29, m({M,H}) = 0.02, m({H}) = 0.5, m({VH}) = 0.04, m(θ) = 0.14	2.46	0.68	0.038
C_{23}	m({VL] = 0.001, m({L}) = 0.01, m({M,L}) = 0.05, m({M}) = 0.05, m({H}) = 0.15, m({H,VH}) = 0.01, m(θ) = 0.72	4.46	0.42	0.023
C_{24}	m({M}) = 0.13, m({M,H}) = 0.19, m({H}) = 0.22, m({H,VH}) = 0.23, m(θ) = 0.23	4.10	0.47	0.026
C_{25}	m({L}) = 0.04, m({M}) = 0.2, m({H}) = 0.01, m({H,VH}) = 0.006, m({VH}) = 0.48, m(θ) = 0.26	3.07	0.6	0.033
C_{26}	m({VL}) = 0.004, m({L}) = 0.009, m({M,L}) = 0.001, m({M}) = 0.009, m({H}) = 0.27, m({VH}) = 0.44, m(θ) = 0.26	2.99	0.61	0.034
C_{31}	m({VH}) = 1, m(θ) = 0	0	1	0.055
C_{32}	m({VL}) = 0.005, m({M,L}) = 0.02, m({M}) = 0.51, m({VH}) = 0.1, m(θ) = 0.36	3.32	0.57	0.032
C_{33}	m({VL}) = 0.002, m({L}) = 0.002, m({M}) = 0.34, m({H}) = 0.42, m(θ) = 0.23	2.72	0.65	0.036
C_{34}	m({VL}) = 0.002, m({L}) = 0.11, m({M,L}) = 0.004, m({M}) = 0.2, m({H}) = 0.4, m(θ) = 0.23	3.30	0.57	0.032
C_{35}	m({VL}) = 0.003, m({M,L}) = 0.002, m({H}) = 0.84, m({H,VH}) = 0.001, m(θ) = 0.11	1.16	0.85	0.047
C_{36}	m({L}) = 0.001, m({M}) = 0.003, m({M,H}) = 0.12, m({H}) = 0.61, m({H,VH}) = 0.07, m({VH}) = 0.01, m(θ) = 0.09	2.23	0.71	0.039
C_{41}	m({VH}) = 1, m(θ) = 0	0	1	0.055
C_{42}	m({VL}) = 0.0009, m({L}) = 0.01, m({M}) = 0.14, m({H}) = 0.31, m({H,VH}) = 0.1, m({VH}) = 0.23, m(θ) = 0.2	3.43	0.56	0.031

Table 8. *Cont.*

Criteria	Combined BPA	E_j	D_j	w_j
C_{43}	m({VL}) = 0.001, m({L}) = 0.001, m({M}) = 0.29, m({M,H}) = 0.0004, m({H}) = 0.45, m({H,VH}) = 0.01, m({VH}) = 0.18, m(θ) = 0.23	3.22	0.58	0.032
C_{44}	m({L] = 0.009, m({M}) = 0.12, m({H}) = 0.23, m({H,VH}) = 0.009, m({VH}) = 0.28, m(θ) = 0.35	3.77	0.51	0.028
C_{45}	m({VL}) = 0.001, m({VL,L}) = 0.007, m({L}) = 0.17, m({M}) = 0.007, m({H,VH}) = 0.09, m({VH}) = 0.05, m(θ) = 0.67	4.93	0.36	0.020
C_{46}	m({VH}) = 1, m(θ) = 0	0	1	0.055

The weights of criteria reported in Table 8 are used to obtain the normalized-weighted decision-making matrix. According to the results of Table 8, the weight values of the economic, socio-cultural, environmental, and technical criteria are equal to 0.327, 0.209, 0.241, and 0.221, respectively. The weight value of each criterion is equal to the sum of the weight value of its sub-criteria. The results reveal the economic criteria are the most important in the material selection process.

Among the criteria for evaluating the sustainability of materials, design and construction time (C_{11}), operational cost (C_{12}), cost of maintenance/repairs/service (C_{13}), transportation cost (C_{17}), greenhouse gases (C_{35}), and weight of material (C_{41}) are considered as the cost type criteria and the rest are the profit criteria. In our case, the optimal value is used as $x_{0j} = 5$ for the benefit type criteria, and it is considered as $x_{0j} = 1$ for the cost type criteria. Finally, the optimality function and alternative utility are calculated and presented in Table 9. The last column of Table 9 shows the rank of alternatives. Table 9 presents objective 4 of the paper. According to the results, aluminum siding (A_1) is the best sustainable material that can be used for a building façade. Clay brick (A_2) is determined as the second sustainable material for a building facade. Furthermore, stone facade (A_5), brick and mortar walls (A_4), and glass facade (A_3) were ranked third to fifth, respectively, in terms of sustainability.

Table 9. ARAS results.

Alternative	S_i	K_i	Rank
A_0	0.290	1.000	-
A_1	0.156	0.538	1
A_2	0.143	0.494	2
A_3	0.131	0.450	5
A_4	0.137	0.472	4
A_5	0.140	0.482	3

6. Conclusions

In this paper, an evidential model was developed based on the Dempster-Shafer theory of evidence and the ARAS method for the sustainable building material selection problem under uncertainty. The experts' assessment and their confidence levels are used to construct the BPAs. The evidential model supports the decisions when information is unclear or conflicts. It was the first attempt to apply the DS evidence theory to solve the sustainable material selection problem. Furthermore, the ARAS method was employed to prioritize five sustainable materials in building facades. Integrating the DS theory and the ARAS method can deal with uncertain information effectively and provides a reasonable solution for the sustainable material selection problem.

Deng entropy was utilized to calculate the weights of criteria and their sub-criteria. The weight values of the economic, socio-cultural, environmental, and technical criteria were calculated as 0.327, 0.209, 0.241, and 0.221, respectively. These results show that economic criteria are the most important criteria in the sustainable material selection process. According to the results of the ARAS method, the alternative utility values for aluminum siding (A_1), clay brick (A_2), and stone facade (A_5) are equal to 0.538, 0.494, and 0.482, respectively. These results reveal that aluminum siding is the best sustainable material among the five materials studied in this article. Clay brick (A2) and stone facade (A5) are in the second and third rank values in terms of sustainability, respectively.

It is worth mentioning that the effectiveness of the proposed DS evidence theory and ARAS method is illustrated through a real case study. In future research, the proposed method should be applied to more practice to further verify its feasibility. In some cases where there are conflicts among evidence, the results may be unreliable. Therefore, the existence of conflicts can be considered as one of the limitations of using evidence theory. It is an interesting topic for future research to develop a modified model based on the evidence theory to solve the sustainable material selection problem by considering the conflicts.

Appendix A

Table A1. The definition of the variables and notations.

Symbol	Description	Symbol	Description
θ	The frame of discernment	$|A|$	The cardinality of proposition A
$H_1, H_2, \ldots., H_n$	hypotheses	$BetP\{x\}$	The pignistic probability transformation for $x \in \theta$
2^θ	The power set of θ	X	The decision-making matrix
A	a member of the power set	x_{ij}	The rating of alternative i for criterion j
$m(A)$	The mass function of A	x_{0j}	The optimal value of j th criterion

Table A1. *Cont.*

Symbol	Description	Symbol	Description
$E(BPA)$	Deng entropy for a BPA or a mass function	$\overline{X}$	The normalized decision-making matrix
$E_{\max}$	Maximum value of Deng entropy	$\hat{X}$	The normalized-weighted decision-making matrix
F_i	A proposition in mass function	w_j	The weight of j th criterion
$\|F_i\|$	The number of elements of F_i	D_j	The consistency of alternatives for j criterion
$w(BPA)$	The weight of a given BPA	E_j	The entropy of j criterion
α	Discounting coefficient	S_i	The optimality function of alternative i
$m^{\alpha}(A)$	The discounted BPA for A	K_i	The alternative utility
$m^{\alpha}(\theta)$	The discounted BPA for θ	$A_1, A_2, \ldots, A_m$	Alternatives
k	The conflict between two BPAs	$C_1, C_2, \ldots, C_n$	criteria

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