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A Quantitative Group Decision-Making Methodology for Structural Eco-Materials Selection Based on Qualitative Sustainability Attributes

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Abstract: In response to escalating global environmental challenges, developed countries have embarked on an ecological transition across a range of sectors. Among these, the construction industry plays a key role due to its extensive use of raw materials and energy resources. In particular, research into sustainable construction materials, here named eco-materials, has seen a boost in recent years because of their potential to replace less environmentally friendly materials such as concrete and steel. This paper proposes a large-scale group decision-making methodology to select among a set of candidate structural eco-materials based on sustainability considerations. The proposed approach is based on a novel quantitative SWOT analysis using survey data from a diverse group of experts, considering not only the technical aspects of the materials but also their impact in the context of the United Nations' Sustainable Development Goals. As a result, a range of eco-materials are probabilistically assessed and ranked, taking into account the variability and uncertainty in the survey data. The results of this research demonstrate the suitability of the proposed methodology for eco-material selection based on sustainability criteria, but also provide a new generic methodology for group decision assessment considering the uncertainty in the survey data, which can be extended to multiple applications.

Keywords: eco-materials; multiple criteria decision-making; probabilistic models; quantitative SWOT analysis; Sustainable Development Goals; uninorms

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1. Introduction

The sustainable use of energy and natural resources is an essential component of resilient and modern societies. The construction industry plays a key role in this endeavor, since it accounts for over 30% of natural resource extraction and contributes to 25% of solid waste generation [1]. In addition, the construction sector is a major consumer, consuming approximately 40% of the world's energy supply and 12% of the world's water resources [2,3]. Due to these negative impacts, the construction industry and researchers in this field are increasingly challenged to find ways to reduce such impacts, and there is an increasing research focus on the exploration of sustainable, environmentally friendly building materials, referred to here as *eco-materials*.

A universally accepted global definition of eco-materials remains elusive; however, broadly speaking, any material that exhibits environmental attributes, such as low carbon emissions, minimal embodied energy, and recyclability, can be classified as an eco-material [4]. A building material achieves this classification when it undergoes a comprehensive evaluation of its life cycle through a Life Cycle Assessment (LCA) and formally demonstrates sustainability [5]. In recent years, a number of countries have implemented regulations aimed at fostering the utilization of environmentally friendly materials in construction, with variations observed from one country to another. Within the European Union, sustainable materials are promoted through directives such as the Energy Performance of Buildings Directive [6] and the Construction Products Regulation (CPR) [7]. France, for instance, has introduced the RE2020 regulation [8] to promote eco-materials and energy efficiency, while Germany employs standards and certification procedures facilitated by the German Sustainable Building Council (DGNB) [8]. In pursuit of eco-materials and sustainable construction practices, the United Kingdom, Canada, China, Australia, Japan, and Brazil have each established their own sets of regulations and certification programs; an overview of these can be found in [9,10]. In the United States, green building rating systems, such as Leadership in Energy and Environmental Design (LEED), have been instituted to provide project management teams with a comprehensive framework aimed at facilitating the achievement of more sustainable developments, complemented by localized state regulations [11]. Besides these regulations and initiatives, the widespread use of eco-materials in construction is still quite limited for a number of reasons, the most important ones being the lack of comprehensive data and information about the long-term behavior of these materials [12,13] and the absence of rational and comparable criteria to determine the advantages and disadvantages of sustainable building materials and their feasibility to replace conventional building materials in construction projects [14,15].

To date, the selection of the most appropriate sustainable building material is fundamentally dependent on the (subjective) expertise and judgment of the designer, as well as the preferences of the project owner [16]. This choice must take into account a wide range of factors, including but not limited to structural strength requirements, sustainability attributes, economic considerations, aesthetics, and a wide variety of other project-specific variables [17,18]. Indeed, as the range of available eco-materials expands and their properties exhibit a wide range of variation, such a selection process becomes increasingly complex and multifaceted. These arguments call for a rational and reproducible decision-making methodology for eco-material selection and ranking, covering objective aspects such as the cost and mechanical performance of the materials, but also less objective attributes such as expert opinions, impacts on sustainability, or aesthetics, in a rigorous and principled way. Indeed, the literature offers a wide variety of methodologies and frameworks designed to facilitate building material selection based on quite different criteria. For example, Arroyo et al. [19] propose a systematic approach to sustainable material selection using the *choosing by advantages* method, and they illustrate its application through the selection of ceiling tiles for construction. Chen et al. [20] introduce a hybrid model for multi-criteria group decision-making that aids designers and engineers in selecting sustainable building materials. Their methodology is based on a novel linguistic approach for modeling and processing subjective information integrated within an consensus reaching methodology [21]. Akadiri et al. [22] develop computational methodologies to facilitate the systematic selection of sustainable materials based on the integration of different evaluation criteria and analytical models to enable informed decision-making. Sahlol et al. [23] propose a method to simulate the behavior of the sustainability parameters of building materials, to evaluate and select among a set of candidates using *system dynamics modeling*. Figueiredo et al. [24] propose an integrated approach for sustainable material selection that combines Life Cycle Sustainability Assessment, Building Information Modeling, and Multi-Criteria Decision Analysis.

This paper aims to answer the research question of how to make a rational decision when choosing the most appropriate sustainable building material. More specifically, the main research objective is to develop a quantitative group decision-making methodology for structural material selection based on qualitative sustainability attributes. To achieve this, a rational methodology for multiple-criteria large-scale group decision-making under uncertainty in application to the selection of the most suitable eco-material among a set of candidates is developed. The proposed approach is grounded on a novel quantitative *strengths, weaknesses, opportunities, and threats* (SWOT) analysis methodology, using survey data collected from a diverse group of experts and stakeholders that consider both the objective and subjective attributes of the materials in the context of their impacts on the United Nations' Sustainable Development Goals (SDGs). SWOT analysis is a qualitative method that lacks the capability to facilitate comparative analysis using quantitative metrics. In this sense, a domain-specific multiple-criteria decision-making (MCDM) model is developed along with the adoption of novel mixed-behavior aggregation functions, which are able to capture the dual nature and interrelationships between the surveyed SWOT factors accounting for the uncertainty in the data. The proposed methodology is demonstrated using data from three candidate eco-materials, namely *rammed earth*, *hempcrete*, and *ferrock*. The experts and stakeholders involved in the survey include engineering academics and practitioners in different countries.

The results demonstrate the suitability of the proposed methodology in selecting and ranking among a set of candidate eco-materials by aggregating heterogeneous and subjective information from survey data and transforming it into quantitative scores that allow for rational decision-making. Importantly, the proposed methodology for group decision-making is generic and can be easily adapted to different disciplines and selection processes by simply adapting the required SWOT analysis.

The rest of the paper is organized as follows: Section 2 provides an overview of the SDGs as well as an overview of the analyzed eco-materials; the methodology for large-scale group decision-making based on a quantitative SWOT analysis is shown in Section 3; the results and discussion are provided in Section 4; finally, conclusions are drawn in Section 5.

2. Background

2.1. Overview of SDGs

The United Nations member states have established a set of seventeen (17) Sustainable Development Goals (SDGs) as the foundational principles of the *2030 Agenda for Sustainable Development*. The SDGs remain the same for all nations, regardless of their current level of development (2030 Agenda for Sustainable Development: https://sustainabledevelopment.un.org/post2015/transformingourworld (accessed on 1 November 2022)). These goals include eliminating poverty and hunger, protecting the environment and its limited resources, reducing vulnerabilities, and addressing social inequalities, among other pressing issues [25]. An overview of the SDGs is provided in Table 1. They represent a concerted effort to tackle multifaceted global challenges and foster a more sustainable and equitable future for all [26]. Through a comprehensive analysis of the inherent nature and fundamental rationale of each of these 17 goals and their corresponding *targets*, construction and building materials are found to significantly impact the attainment of several SDGs, particularly SDGs 7, 8, 12, and 13. The following section provides an overview of the sustainable attributes associated with the selected eco-materials in the context of the SDGs, which is used as input to define the SWOT analysis required in the proposed decision-making methodology, as explained in Section 4.1.

Table 1. The seventeen Sustainable Development Goals (SDGs). Further information is found in https://sdgs.un.org/goals (accessed on 1 February 2023).

United Nations Sustainable Development Goals
Goal 1: No poverty *- End poverty in all its forms everywhere.*
Goal 2: Zero hunger *- End hunger, achieve food security and improved nutrition and promote sustainable agriculture.*
Goal 3: Good health and wellbeing *- Ensure healthy lives and promote wellbeing for all at all ages.*
Goal 4: Quality education *- Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.*

Table 1. *Cont.*

United Nations Sustainable Development Goals
Goal 5: Gender equality *- Achieve gender equality and empower all women and girls.*
Goal 6: Clean water and sanitation *- Ensure availability and sustainable management of water and sanitation for all.*
Goal 7: Affordable and clean energy *- Ensure access to affordable, reliable, sustainable and modern energy for all.*
Goal 8: Decent work and economic growth *- Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.*
Goal 9: Industry, innovation and infrastructure *- Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.*
Goal 10: Reduced inequalities *- Reduce inequality within and among countries.*
Goal 11: Sustainable cities and communities *- Make cities and human settlements inclusive, safe, resilient and sustainable.*
Goal 12: Responsible consumption and production *- Ensure sustainable consumption and production patterns.*
Goal 13: Climate action *- Take urgent action to combat climate change and its impacts.*
Goal 14: Life below water *- Conserve and sustainably use the oceans, seas and marine resources for sustainable development.*
Goal 15: Life on land *- Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.*
Goal 16: Peace, justice and strong institutions *- Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.*
Goal 17: Partnerships for the goals *- Strengthen the means of implementation and revitalize the global partnership for sustainable development.*

2.2. Overview of Eco-Materials for Sustainable Building

Improving building sustainability has become increasingly important as it has a positive impact on the economy, society, and the environment [27,28]. The sustainable building challenge consists of four main factors, which include utilizing natural resources such as energy, water, land, and building materials; creating healthy surroundings both indoors and outdoors; designing buildings and communities; and assessing environmental effects, including construction processes, life cycle operations, and deconstruction [29]. Eco-materials are typically sourced from renewable or recycled materials, which helps to minimize the need to extract limited resources and reduces waste [30–33]. By using these environmentally friendly materials, the preservation of resources becomes a significant benefit gained [34]. These materials are crucial in promoting sustainable construction practices as they can help to mitigate the environmental impacts associated with traditional building materials. Locally sourced materials in building also play a major role in reducing the environmental impact. For instance, energy consumption and transportation activities in a house built with local materials were reduced by 215% and 453%, respectively, when compared to a house not built with local materials [35]. Therefore, the use of locally sourced materials and non-manufactured building materials for construction is crucial to minimize transportation distances. This not only reduces air pollution caused by vehicles but also supports local economic activities [36,37].

Using eco-friendly materials in sustainable building projects usually requires more effort than in conventional projects [38]. This usually includes creating agreements that ensure environmentally responsible practices and materials used, along with strict management and control measures on the site. These contracts are very important in upholding the commitment to sustainable principles throughout the life cycle of the project and ensuring that eco-materials are effectively integrated into the construction process [39,40]. In this sense, sustainable construction methods are more complicated most of the time [41]. This problem is exacerbated in developing nations [42], where the potential of these sustainable materials can be very significant, due to issues such as a lack of water supply systems, shortcomings in education, low wages, restricted access to advanced technology and skills, and limitations in the construction industry's ability to adopt sustainable practices [27,43].

A number of sustainable building materials have been explored during recent decades for sustainable construction, including bamboo, cork, ferrock, hempcrete, mycelium, papercrete, rammed earth, strawbale, etc. However, rammed earth, hempcrete, and ferrock have attracted the attention of eco-materials researchers due to their good mechanical and thermal performance and their strong potential to replace cement-based materials in the near future [44]. In this sense, these materials will be further discussed and analyzed in the upcoming sections.

2.2.1. Rammed Earth

The term "rammed earth" refers to the historical construction technique or methods in which the materials (earth) are rammed in layers, being the soil its main component [45,46]. The rammed earth is based on a mixture of gravel, sand, silt, and clay, which are wetted to reach optimum moisture and then compacted by layers inside formworks to achieve a homogeneous and continuous wall structure [47]. Some examples of historic rammed earth buildings are the Alhambra in Granada (Spain) and the Potala Palace in Tibet (China).

Rammed earth structures can be constructed using natural soil (unstabilized rammed earth) without additives [48,49], whose compressive strength is relatively low (1.0 MPa to 2.5 MPa) [49], resulting in thick-walled structures. To overcome this limitation, stabilizing materials such as cement or lime are added to rammed earth mixes (stabilized rammed earth) [50,51], and sometimes waterproofing agents are added to reduce erosion from rain [49]. The use of rammed earth reduces energy consumption during construction because of the availability of raw materials and the simplicity of preparation [52].

The rammed earth construction has seen a number of codes and standards that have been approved by some countries, but, due to the different types of soils and climate differences around the world, it is difficult to create codes or standards that are internationally appropriate for all countries [53]. Australia was one of the first countries to produce a national design and construction code for rammed earth. The first edition, named *Bulletin 5*, was developed in 1952 by the Commonwealth Experimental Building Station [54]. Germany was also one of the first countries to publish rammed earth codes and standards, between 1947 and 1956. In 1999, the *Lehmbau Regeln* (German rules for earthen architecture) [55] was developed, a national document that includes general requirements for earthen structures and rammed earth, suitable soil types, appropriate tests, construction methods, design procedures, etc. New Zealand published three codes for unfired earthen building materials (including rammed earth) in 1998: the first code for earth walls of 6.5 m height or less, the second code for earth walls up to 3.3 m height for seismic zones, and the last code specialized in soil and cement mixtures [56]. In Spain, the Ministry of Transport and Public Works published, in 1992, guidelines for the design and construction of earthen structures, focusing mainly on rammed earth [57]. The New Mexico Building Code of 1991 contains methods of construction, testing, and curing for rammed earth [58]. Finally, Zimbabwe made a significant step in promoting rammed earth construction by publishing a standard code of practice in 2001 [59]. Figure 1 [60] shows an example of rammed earth construction (left panel), along with a scheme of the construction process for a rammed earth walled structure (right panel).

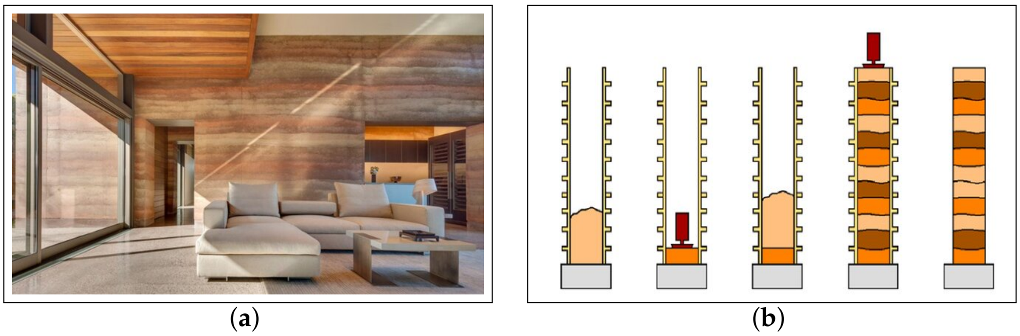

(**a**) (**b**)

Figure 1. Example of rammed earth construction. (**a**) House made of rammed earth in New Mexico. (**b**) The process of building a rammed earth wall.

2.2.2. Hempcrete

Climate change in recent years has pushed the world to find some vegetal concrete that uses biomass, yielding benefits such as decreasing the carbon effects, renewability, and low embodied energy [61]. One of the most researched bio-based concretes is hemp concrete, or *hempcrete*, which is made of recyclable resources such as lime, water, and hemp shivs mixed together in three stages (spraying, mixing or molding, and tamping) [62]. Hempcrete use is not new, as it was used in bridges in Southern France in the 6-*th* century, and its modern use in France began in 1990 for the rehabilitation of historic timber-framed buildings [63]. These hempcrete applications demonstrate the durability and suitability of the material [64,65].

According to the literature, the compressive strength of hemp-fiber-reinforced concrete can reach up to 35 MPa, which is comparable to that of traditional concrete. However, the strength of the material decreases as the density decreases [66]. Additionally, it has been noted that hemp-fiber-reinforced concrete has less workability compared to traditional concrete [63]. Hempcrete is used as sound and thermal insulation, as a reinforcing shiv for plasters and prefabricated building materials [65], to control the indoor environment [67], and to reduce greenhouse gas emissions [64]. However, hempcrete performs as well as conventional building materials in warmer weather, which implies that more energy is required to maintain a comfortable building temperature in cold conditions [68]. Moreover, it holds too much water and absorbs it for a long time [61], requiring an efficient working process to avoid any negative effects from increasing setting and drying times.

To the best of the authors' knowledge, there are no official standards, guidelines, or procedures for hempcrete [67,69]. Thus, the on-site installation process of hempcrete would require *ad–hoc* testing and certification. However, the growing interest in hempcrete will prompt the industry to create new certification processes and open new business opportunities [65], and, as technology advances, the economic and sustainable performance of hempcrete is expected to improve [68]. Figure 2 shows an example of a construction using hempcrete (left panel) and an image of the construction process using hempcrete blocks (right panel).


(**a**) (**b**)

Figure 2. Hempcrete construction examples. (**a**) House made of hempcrete in Nevada City, CA, USA. (**b**) The process of building a hempcrete wall. Images taken from www.hempbuildmag.com (accessed on 15 October 2023).

2.2.3. Ferrock

Another relevant example of a sustainable building material is ferrock, which is a mixture of iron powder, lime, fly ash, oxalic acid, and metakaolin [70]. The ferrock technology was introduced at the University of Arizona, where, while researching an alternative material to cement that had similar strength and workability, they discovered that iron reacts with CO_2 to create iron carbonate to form ferrock [71]. Ferrock is a carbon-negative material compared to Portland cement, which is the primary source of CO_2 emissions and air pollution during its manufacturing process [72]. In this sense, ferrock is considered a partial replacement material for cement [71], and tests showed that after 28 days, the compressive, flexural, and tensile strengths of ferrock concrete (8% replacement ratio) were improved by 12% compared to normal mixes [70,73]. Moreover, it has better crack resistance and increased fire and thermal resistance [74]. The slump value of ferrock as a replacement for concrete is in accordance with the mix design specifications [75]. Nevertheless, ferrock's iron powder contains microparticles that pose health risks during the manufacturing process [71], and although it is cheaper than concrete, its price could see a significant increase if the demand for ferrock increases [76].

Ferrock is a relatively new material [77] and there are no published official codes for design and construction using it. In addition, it has only been tested for small projects, and its performance in large projects is still unclear [76]. Figure 3 shows an example of construction using ferrock (left panel) and an illustration of the construction process using this material (right panel).


(**a**) (**b**)

Figure 3. Ferrock construction examples. (**a**) Dome structure made of ferrock in USA. Picture taken from https://www.certifiedenergy.com (accessed on 15 October 2023). (**b**) The process of building a ferrock wall. Picture taken from https://www.pbs.org (accessed on 15 October 2023).

3. Large-Scale Group Decision-Making Methodology

In this research, a large-scale group decision-making methodology to select among a set of candidate eco-materials based on sustainability considerations is developed. Figure 4 shows a flowchart of the different stages of the method. First, a set of candidate eco-materials is selected, namely rammed earth, hempcrete, and ferrock, and a literature review and an analysis from the SDG perspective are performed (see Section 2.2). Next, the SWOT analysis is carried out to define the different SWOT factors and items for each eco-material (see Section 4.1). Simultaneously, an online survey is designed by defining the target audience, as well as the scoring criteria for the different SWOT items. The online survey is sent to the selected set of experts to ascertain their opinions regarding the proposed SWOT items in light of the SDGs. The selected audience can be heterogeneous (e.g., researchers, industry experts, policy makers, etc.), in which case different weights can be assigned to each group in order to modulate their responses. Finally, a uninorm-based method is adopted to score the experts' opinions and therefore select the best eco-material from a sustainability perspective. This method is described in Section 3.2.

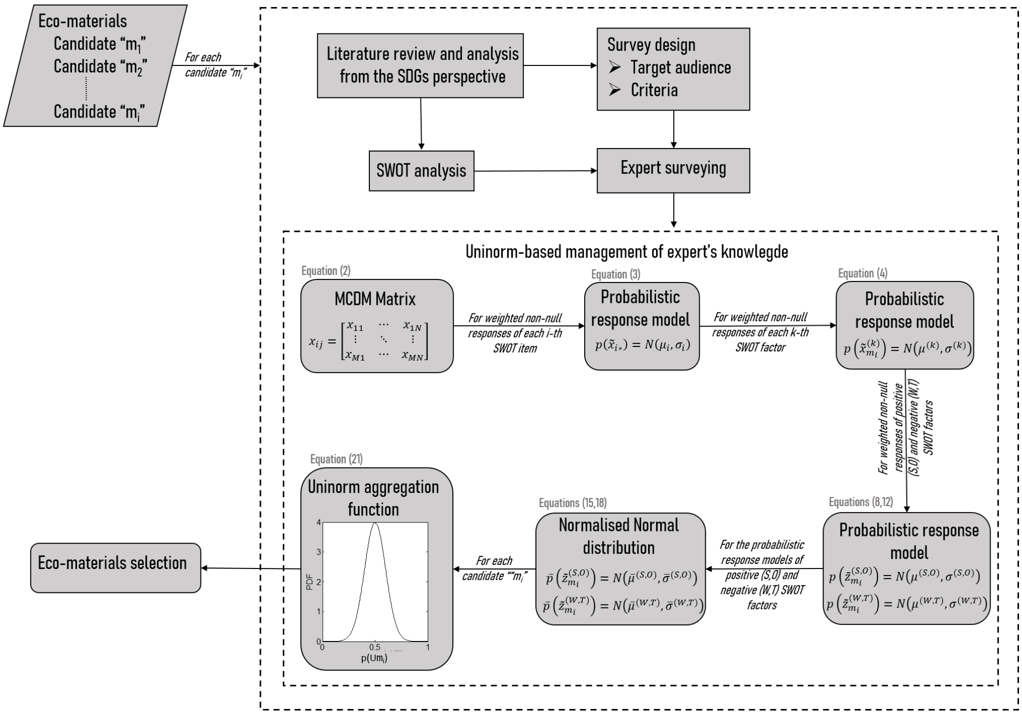


Figure 4. Scheme of the uninorm-based method to manage the experts' knowledge and select the eco-material.

3.1. SWOT Analysis of Eco-Materials from SDG Perspective

SWOT analysis is a powerful tool used mainly in strategic management and planning in organizations [78]. The "SWOT" term symbolizes four components, namely strengths, weaknesses, opportunities, and threats. The strengths and weaknesses represent the internal factors or organizational factors, and the opportunities and threats represent the external factors or environmental factors [78,79]. Strengths and opportunities are beneficial in achieving organizational goals; this is the positive aspect of SWOT factors. On the other hand, weaknesses and threats are adverse to achieving organizational objectives, representing the negative aspect of SWOT factors [78]. The selection of SWOT items for each factor (strengths, weaknesses, opportunities, and threats) is carefully guided by an extensive literature review. This process depends primarily on assessing the advantages or disadvantages associated with sustainability considerations, particularly alignment with the SDGs, for each eco-material. By systematically evaluating these attributes, the SWOT analysis can provide a sophisticated and data-driven perspective on the suitability and potential challenges of eco-materials in different contexts, contributing to informed decision-making in sustainable building practices. It is important to emphasize that not all SWOT factor elements necessarily align with specific SDGs or their targets. This divergence is due to the fact that certain SWOT factors associated with eco-materials may include advantages or disadvantages that go beyond the scope of the SDGs, touching on broader areas of concern and sustainability considerations. The results of the SWOT analysis for the eco-materials considered can be found in Tables 2–4 in Section 4.1.

3.2. Uninorm-Based Method to Manage Experts' Knowledge and Select an Eco-Material

SWOT analysis is a qualitative method that lacks the capability to facilitate comparative analysis using quantitative metrics. In this sense, a domain-specific multiple-criteria decision-making (MCDM) model is developed along with the use of mixed-behavior aggregation functions, which are able to capture the dual nature and interrelationships between SWOT factors in their evaluation process. To this end, the data obtained from the experts for each eco-material are processed to build a MCDM *decision matrix*.The MCDM matrix is composed of a set of submatrices related to the different SWOT factors. For each eco-material, the MCDM matrix is composed as follows:

$$\mathbf{X}_m = \begin{bmatrix} \mathbf{X}_m^{(S)} \\ \mathbf{X}_m^{(W)} \\ \mathbf{X}_m^{(O)} \\ \mathbf{X}_m^{(T)} \end{bmatrix} \tag{1}$$

where $m = \{m_1, m_2, m_3\}$ denotes the different eco-materials considered, and the superscripts S, W, O, T denote the SWOT factors (strengths, weaknesses, opportunities, and threats, respectively). The submatrix for each SWOT factor ($\mathbf{X}_m^{(S)}, \mathbf{X}_m^{(W)}, \mathbf{X}_m^{(O)}, \mathbf{X}_m^{(T)}$) is composed of the data obtained from the online survey, and it is organized as follows [80]:

$$\mathbf{X}_m^{(k)} = \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1N} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{iN} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{M1} & \cdots & x_{Mj} & \cdots & x_{MN} \end{bmatrix} \tag{2}$$

where superscript k serves to indicate the SWOT factor being considered, i.e., $k = \{S, W, O, T\}$; x_{ij} is the response of the *j-th* expert to the *i-th* SWOT item (a SWOT item is one of the statements that defines a particular SWOT factor, e.g, "Fire resistance and good acoustic insulation" in Table 2); $i = \{1, \cdots, M\}$ and $j = \{1, \cdots, N\}$, with M and N being the SWOT items considered and the number of surveyed experts, respectively; and the subscript m serves to indicate the eco-material considered, i.e., $m = \{m_1, m_2, m_3\}$. Next, the x_{ij} values are re-sampled based on the weights assigned to take into account the areas of knowledge of the experts. For the sake of simpler notation, the superscript (k) and the subscript m are not made explicit in Equation (2) and the following, unless otherwise stated.

Under the assumption that the number of experts M is large enough (which is why the method is called the *large-scale group decision-making method*), a Gaussian probability model can be adopted to represent the non-null responses of the experts for the *i-th* SWOT item, as follows:

$$p(\tilde{x}_{i*}) = \mathcal{N}(\mu_i, \sigma_i) \tag{3}$$

where $\tilde{x}_{i*}$ is an uncertain variable representing the non-null responses of the experts for the *i-th* SWOT item, i.e., $\tilde{x}_{i*} \in [x_{min}, x_{max}]$, where $x_{min} \in \mathbb{R}^+$, and $x_{max} \in \mathbb{R}^+$ are the maximum and minimum positive responses for the *i-th* SWOT item (in this work, $x_{min} = 1$ and $x_{max} = 9$). In Equation (3), the mean μ_i and standard deviation σ_i are obtained using the Maximum Likelihood Estimate (MLE) method from the data x_{i*}, contained in the *i-th* row of $\mathbf{X}_m^{(k)}$ (Equation (2)), corresponding to the *i-th* SWOT item and the *k-th* SWOT factor. From this standpoint, a single probabilistic response model representing the non-null responses of the M experts for the *k-th* SWOT factor is obtained by aggregating the M non-null response models obtained by Equation (3) as follows:

$$p(\tilde{x}_m^{(k)}) = \mathcal{N}(\mu^{(k)}, \sigma^{(k)}) \tag{4}$$

with

$$\mu^{(k)} = \sum_{i=1}^{M} \mu_i w_i / \sum_{i=1}^{M} w_i \tag{5}$$

and

$$\sigma^{(k)} = \sqrt{\sum_{i=1}^{M} (\sigma_i w_i)^2 / \sum_{i=1}^{M} w_i^2} \tag{6}$$

where $\tilde{x}_m^{(k)}$ represents the non-null responses of the M experts for the *k-th* SWOT factor and the *m-th* eco-material. In Equations (5) and (6), $\mu^{(k)}$ and $\sigma^{(k)}$ are obtained from the mean (μ_i), standard deviation (σ_i), and the number of non-null responses (w_i) of each *i-th* SWOT item, respectively. Note that, in this case, μ_i and σ_i are obtained from Equation (3) for the *i-th* SWOT item.

The next step involves obtaining a probability response model for the positive SWOT factors (e.g., S and O) that correspond to the *m-th* eco-material, based on the non-null responses of the group of experts. To this end, a new uncertain variable $\tilde{z}_m^{(S,O)}$ is defined, which represents the non-null responses of the experts for factors $k = S$ and $k = O$, given by

$$\tilde{z}_m^{(S,O)} = 0.5\tilde{x}_m^{(S)} + 0.5\tilde{x}_m^{(O)} \tag{7}$$

From this standpoint, the probabilistic model representing the overall non-null responses of the experts for the positive SWOT factors and the *m-th* eco-material can be obtained as

$$p(\tilde{z}_m^{(S,O)}) = \mathcal{N}(\mu^{(S,O)}, \sigma^{(S,O)}) \tag{8}$$

with

$$\mu^{(S,O)} = 0.5\mu^{(S)} + 0.5\mu^{(O)} \tag{9}$$

and

$$\sigma^{(S,O)} = \sqrt{(0.5\sigma^{(S)})^2 + (0.5\sigma^{(O)})^2} \tag{10}$$

where $\mu^{(k)}$ and $\sigma^{(k)}$ are the mean and the standard deviation obtained from Equations (5) and (6) for $k = S$ and $k = O$.

Similarly, a single probabilistic response model for the negative SWOT factors (represented by $k = W, T$) of the *m-th* eco-material, based on the uncertain variables of the non-null responses provided by the experts, is obtained. The new uncertain variable $\tilde{z}_m^{(W,T)}$, which represents the non-null responses of the experts ($\tilde{x}_m^{(k)}$) for $k = W$ and $k = T$ factors, is defined as follows:

$$\tilde{z}_m^{(W,T)} = 0.5\tilde{x}_m^{(W)} + 0.5\tilde{x}_m^{(T)} \tag{11}$$

Therefore, the probability model of the non-null responses of the experts for the negative SWOT factor and the *m-th* eco-material is obtained as

$$p(\tilde{z}_m^{(W,T)}) = \mathcal{N}(\mu^{(W,T)}, \sigma^{(W,T)}) \tag{12}$$

with

$$\mu^{(W,T)} = 0.5\mu^{(W)} + 0.5\mu^{(T)} \tag{13}$$

and

$$\sigma^{(W,T)} = \sqrt{(0.5\sigma^{(W)})^2 + (0.5\sigma^{(T)})^2} \tag{14}$$

where $\mu^{(k)}$ and $\sigma^{(k)}$ are the mean and the standard deviation obtained from Equations (5) and (6) for $k = W$ and $k = T$.

Based on this, the normal distribution functions from the positive and negative SWOT factors (Equations (8) and (12)) are normalized taking into account the assigned values in the online survey as "not relevant" (x_{min}) and as "relevant" (x_{max}). In the case of positive factors ($k = S, O$), the normalization is

$$\bar{p}(\tilde{z}_m^{(S,O)}) = \mathcal{N}(\bar{\mu}^{(S,O)}, \bar{\sigma}^{(S,O)}) \tag{15}$$

with

$$\bar{\mu}^{(S,O)} = \frac{\mu^{(S,O)} - x_{min}}{x_{max} - x_{min}} \tag{16}$$

and

$$\bar{\sigma}^{(S,O)} = \frac{\sigma^{(S,O)}}{x_{max} - x_{min}} \tag{17}$$

where $\mu^{(S,O)}$ and $\sigma^{(S,O)}$ are the mean and standard deviation obtained from Equations (9) and (10), respectively.

For the normal distribution function from the negative factors ($k = W, T$), the normalization is

$$\bar{p}(\tilde{z}_m^{(W,T)}) = \mathcal{N}(\bar{\mu}^{(W,T)}, \bar{\sigma}^{(W,T)} \tag{18}$$

with

$$\bar{\mu}^{(W,T)} = 1 - \frac{\mu^{(W,T)} - x_{min}}{x_{max} - x_{min}} \tag{19}$$

and

$$\bar{\sigma}^{(W,T)} = \frac{\sigma^{(W,T)}}{x_{max} - x_{min}} \tag{20}$$

where $\mu^{(W,T)}$ and $\sigma^{(W,T)}$ are the mean and standard deviation obtained from Equations (13) and (14), respectively. In this case, the conversion of the random variable representing the negative factors ($\tilde{z}_m^{(W,T)}$) is performed to convert it into the same scale as the random variable representing the positive factors ($\tilde{z}_m^{(S,O)}$). For example, values close to one could represent positive maxima, while values close to zero could indicate negative maxima. This results in a different expression of $\bar{\mu}^{(W,T)}$ with respect to $\bar{\mu}^{(S,O)}$.

Finally, a representative response model associated with the m eco-material is obtained through the uninorm aggregation function [81] as a tool for multi-criteria decision-making. For this, the random variables representing the non-null responses of the experts for the positive $\tilde{z}_m^{(S,O)}$ and negative $\tilde{z}_m^{(W,T)}$ SWOT factors are aggregated as follows:

$$U_m(\tilde{z}_m^{(S,O)}, \tilde{z}_m^{(W,T)}) = \begin{cases} 0 & (\tilde{z}_m^{(S,O)}, \tilde{z}_m^{(W,T)}) \in \{(0,1),(1,0)\} \\ \frac{\tilde{z}_m^{(S,O)} \tilde{z}_m^{(W,T)}}{\tilde{z}_m^{(S,O)} \tilde{z}_m^{(W,T)} + (1-\tilde{z}_m^{(S,O)})(1-\tilde{z}_m^{(W,T)})} & \text{otherwise} \end{cases} \tag{21}$$

To solve Equation (21) Monte Carlo simulation is needed. In this sense, samples of the random variables $(\tilde{z}_m^{(S,O)}, \tilde{z}_m^{(W,T)})$ are obtained from the probabilistic response models calculated from Equations (15) and (18), and introduced as inputs in Equation (21) to obtain samples from U_m.

4. Results and Discussion

In this section, the proposed methodology is illustrated using survey data from two groups of experts, namely engineering academics and engineering practitioners. First, a SWOT analysis is carried out for the candidate eco-materials; then, the proposed decision-making methodology is applied to transform the expert responses to each of the SWOT items into probabilistic quantitative scores for the candidate eco-material.

4.1. SWOT Analysis of Eco-Materials

A SWOT analysis was carried out for each of the candidate eco-materials, considering both technical and sustainability aspects. The results of the SWOT analysis are presented in Tables 2–4 for rammed earth, hempcrete, and ferrock, respectively. Note that for each SWOT factor (e.g., *strengths*), a variable number of M SWOT items are defined (i.e., the first SWOT item (i = 1) for the strength factor ($k = (S)$) of rammed earth corresponds to $x_1^{(S)}$: "The use of recyclable and biodegradable raw materials in line with SDG 12"). Then, the M SWOT items $(x_1^{(k)}, \ldots, x_M^{(k)})$ for the $k = \{S, W, O, T\}$ factors for each candidate eco-material conform to the questionnaires that were submitted to the group of experts. In this study, a total of 15 experts including academic experts and engineering practitioners from different construction disciplines and countries, participated in the survey. More details about the survey, including expert responses, can be found in Appendix A.

Table 2. SWOT analysis of rammed earth.

Strengths	**Weaknesses**
$x_1^{(S)}$—The use of recyclable and biodegradable raw materials in line with SDG 12 (target 12.5) [49].	$x_1^{(W)}$—Rammed earth construction buildings need further tests and experiments due to variations in natural soil [49,53].
$x_2^{(S)}$—Sufficient mechanical and thermal properties [49].	$x_2^{(W)}$—Requires protection against rainfall to reduce erosion [49].
$x_3^{(S)}$—Lowering the construction cost due to the use of local materials in line with SDG 8 (target 8.4) [45].	$x_3^{(W)}$—There are several local codes and standards, but there is still a lack of international design standards and procedures [53].
$x_4^{(S)}$—Fire resistance and good acoustic insulation [49,82].	$x_4^{(W)}$—Rammed earth characteristics are strongly affected by the hygroscopic environmental conditions and a long time is required for drying [48,83].
	$x_5^{(W)}$—Low compressive strength [49].
Opportunities	**Threats**
$x_1^{(O)}$—The availability of raw materials near the construction site enables a lower carbon footprint from transportation, in line with SDG 12 (target 12.2) [52,84].	$x_1^{(T)}$—Uncertainty about the long-term behavior of the material [49,51].
$x_2^{(O)}$—Creation of local jobs and sustainable economic growth in line with SDG 8 (target 8.2), due to the local availability of raw materials and simplicity of manufacturing [84].	$x_2^{(T)}$—In very cold weather, additional insulation is required [52].
	$x_3^{(R)}$—A specific classification may be needed, leaving many local contractors out of business [35].
	$x_4^{(R)}$—It is difficult to get the project approved by the municipality and other related stakeholders [35].

Table 3. SWOT analysis of hempcrete.

Strengths	**Weaknesses**
$x_1^{(S)}$—Using hempcrete as thermal insulation reduces energy consumption, in line with SDG 7 (target 7.3) [64].	$x_1^{(W)}$—The hempcrete mixture stores too much water, and this elongates the drying process [65].
$x_2^{(S)}$—During the hempcrete construction process, the amount of CO2 removed from the atmosphere is higher than the amount generated, in line with SDG 12 and 13 [85].	$x_2^{(W)}$—As the hempcrete density increases, the thermal conductivity also increases, decreasing thermal insulation [66].
$x_3^{(S)}$—Hempcrete is a recyclable and lightweight material, in line with SDG 12 (target 12.5) [61,68].	$x_3^{(W)}$—The thermal performance of hempcrete is very different in different weather conditions [68].
	$x_4^{(W)}$—Further research and experiments are needed for implementation in the building industry [61,65,68].
Opportunities	**Threats**
$x_1^{(O)}$—Hemp fiber is a good reinforcement material due to its high tensile strength and tolerance for alkali [86].	$x_1^{(T)}$—Due to the organic basis of hempcrete, it could cause chemical reactions with the binder, so additional checks are required [65].
$x_2^{(O)}$—As manufacturing technology develops, the economic and sustainability aspects of hempcrete will be improved in line with SDG 12 (targets 12.2 and 12.5) [68].	$x_2^{(T)}$—Hemp cultivation could change the land use from food and essential product production to biomass for construction and building uses, in contrast with SDG 15 [85].
$x_3^{(O)}$—The shape and the size of hempcrete blocks are very similar to traditional blocks known by professionals, so specialist workers are not needed [65].	

Table 4. SWOT analysis of ferrock.

Strengths	**Weaknesses**
$x_1^{(S)}$—Ferrock production depends on the reaction between iron dust with carbon dioxide and rust, so it is considered a CO2-negative material and has low environmental impacts, in line with SDG 13 [73,74].	$x_1^{(W)}$—Ferrock has limited research, testing, and data information to be widely used in the construction sector [77].
$x_2^{(S)}$—Economical operation through the use of recycled waste iron in landfills, in line with SDG 12 (target 12.5) [74].	$x_2^{(W)}$—It is not suitable for large projects where a huge amount of material is required [76].
$x_3^{(S)}$—Ferrock is stronger than Portland cement and uses less energy, in line with SDG 7 (target 7.3) [76].	$x_3^{(W)}$—Due to the steel manufacturing process and production of shot blasting, iron dust could cause health issues, in contrast with SDG 3 [71].
$x_4^{(S)}$—It uses less water for curing compared with cement, so the time required for curing is also shorter, in line with SDG 6 (target 6.4) and SDG 12 (target 12.2) [76].	
Opportunities	**Threats**
$x_1^{(O)}$—Ferrock could be used for maritime constructions, due to the contact with water, which enhances the rusting operation [73,74].	$x_1^{(T)}$—Ferrock is a partial replacement material for cement in concrete, so considerable environmental impacts still exist [71].
$x_2^{(O)}$—Ferrock concrete has good fire and thermal resistance [74].	$x_2^{(T)}$—Ferrock is a new material that has yet to be tested for long-term projects, and its durability is unknown [76,77].
$x_3^{(O)}$—Ferrock has tensile properties due to iron dust, which enhances the durability and compressive strength of concrete [74].	$x_3^{(T)}$—The ferrock material is related to the steel price and availability, so sometimes it is not available or is an uneconomical solution [76].
$x_4^{(O)}$—It is resistant to rotting, corrosion, and UV radiation [77].	

4.2. Multiple-Criteria Decision-Making Model Results

As described in Section 3.2, the MCDM matrix for a particular eco-material is composed of a set of submatrices associated with the different SWOT factors. For the particular case of rammed earth, the resulting MCDM matrix is described as follows:

$$\mathbf{X}_{m_1} = \begin{bmatrix} \mathbf{X}_{m_1}^{(S)} \\ \mathbf{X}_{m_1}^{(W)} \\ \mathbf{X}_{m_1}^{(O)} \\ \mathbf{X}_{m_1}^{(T)} \end{bmatrix} \tag{22}$$

where m_1 denotes the selected eco-material (rammed earth), and the submatrices $\mathbf{X}_{m_1}^{(S)}$, $\mathbf{X}_{m_1}^{(W)}$, $\mathbf{X}_{m_1}^{(O)}$ and $\mathbf{X}_{m_1}^{(T)}$ contain the scores given by the 15 experts (by columns) for the M SWOT items (by rows), as follows:

$$\mathbf{X}_{m_1}^{(S)} = \begin{bmatrix} 9 & 6 & 9 & 9 & 9 & 8 & 8 & 9 & 0 & 7 & 5 & 7 & 2 & 9 & 6 \\ 6 & 5 & 0 & 5 & 9 & 5 & 9 & 7 & 3 & 6 & 9 & 8 & 2 & 9 & 6 \\ 7 & 7 & 0 & 8 & 9 & 6 & 8 & 7 & 5 & 7 & 5 & 7 & 6 & 9 & 8 \\ 9 & 7 & 0 & 7 & 9 & 0 & 9 & 9 & 8 & 8 & 7 & 7 & 6 & 9 & 6 \end{bmatrix} \tag{23}$$

$$\mathbf{X}_{m_1}^{(W)} = \begin{bmatrix} 6 & 8 & 0 & 7 & 3 & 7 & 6 & 8 & 2 & 9 & 8 & 7 & 8 & 5 & 8 \\ 6 & 4 & 0 & 8 & 3 & 8 & 8 & 9 & 7 & 8 & 6 & 8 & 9 & 2 & 8 \\ 6 & 6 & 0 & 6 & 0 & 7 & 4 & 9 & 9 & 8 & 6 & 7 & 9 & 8 & 8 \\ 6 & 5 & 0 & 6 & 3 & 8 & 6 & 9 & 4 & 5 & 2 & 7 & 9 & 1 & 8 \\ 6 & 7 & 0 & 8 & 5 & 6 & 7 & 9 & 2 & 7 & 5 & 2 & 9 & 1 & 6 \end{bmatrix} \tag{24}$$

$$\mathbf{X}_{m_1}^{(O)} = \begin{bmatrix} 8 & 7 & 9 & 8 & 8 & 8 & 2 & 9 & 4 & 9 & 7 & 6 & 7 & 9 & 8 \\ 8 & 3 & 7 & 9 & 7 & 6 & 9 & 9 & 4 & 5 & 6 & 6 & 8 & 9 & 6 \end{bmatrix} \tag{25}$$

$$\mathbf{X}_{m_1}^{(T)} = \begin{bmatrix} 6 & 2 & 0 & 8 & 1 & 9 & 6 & 5 & 6 & 8 & 2 & 4 & 9 & 0 & 6 \\ 6 & 3 & 0 & 6 & 1 & 8 & 2 & 3 & 6 & 5 & 5 & 4 & 8 & 5 & 7 \\ 2 & 4 & 0 & 4 & 0 & 5 & 3 & 3 & 6 & 6 & 7 & 0 & 8 & 1 & 6 \\ 6 & 8 & 0 & 7 & 0 & 7 & 3 & 9 & 8 & 7 & 3 & 0 & 8 & 1 & 7 \end{bmatrix} \tag{26}$$

In this example, the scores range from 0 to 9, with 0 denoting "unsure", 1 denoting "not relevant", and 9 "completely relevant". Similar submatrices can be easily obtained for the rest of the candidate eco-materials using the survey data detailed in Appendix A. To account for the heterogeneity of the expertise in the group of respondents, a weight of 0.6 is applied to the responses coming from academics and 0.4 to those coming from engineering practitioners. The weighted scores were statistically re-sampled and Gaussian probability models were fit to the resampled data. Tables 5–7 present the probabilistic response models obtained for each SWOT item (third column), which corresponds to Equation (3) in the proposed methodology, specifically $p(\tilde{x}_{i*}^{(k)})$. The probabilistic response models for the *k-th* SWOT factor $p(\tilde{x}_m^{(k)})$ are subsequently obtained according to Equation (4). Results are shown in the fourth columns of Tables 5–7 for rammed-earth, hempcrete, and ferrock, respectively. Finally, the probabilistic response models representing the overall non-null responses of the experts for the positive SWOT factors (denoted by $\bar{p}(\tilde{z}_m^{(S,O)})$ in the proposed methodology, Equation (8)) are shown in the fifth columns of Tables 5–7. The models for the negative SWOT factors (denoted by $\bar{p}(\tilde{z}_m^{(W,T)})$, Equation (12)) are shown in the last columns of Tables 5–7 for rammed earth, hempcrete, and ferrock, respectively.

Table 5. Response models from the SWOT analysis for rammed earth.

SWOT Factor	**SWOT Item**	$p(\tilde{x}_{i*}^{(k)})$	$p(\tilde{x}_m^{(k)})$	$\bar{p}(\tilde{z}_m^{(S,O)})$	$\bar{p}(\tilde{z}_m^{(W,T)})$
S	$x_1^{(S)}$	$\mathcal{N}(7.34, 2.22)$	$\mathcal{N}(7.07, 0.94)$	$\mathcal{N}(0.75, 0.1)$	
	$x_2^{(S)}$	$\mathcal{N}(6.19, 2.39)$			
	$x_3^{(S)}$	$\mathcal{N}(7.03, 1.31)$			
	$x_4^{(S)}$	$\mathcal{N}(7.75, 1.2)$			
O	$x_1^{(O)}$	$\mathcal{N}(7.29, 1.98)$	$\mathcal{N}(7.04, 1.39)$		
	$x_2^{(O)}$	$\mathcal{N}(6.79, 1.94)$			
W	$x_1^{(W)}$	$\mathcal{N}(6.53, 2.21)$	$\mathcal{N}(6.45, 1.03)$		$\mathcal{N}(0.3811, 0.1)$
	$x_2^{(W)}$	$\mathcal{N}(6.89, 2.27)$			
	$x_3^{(W)}$	$\mathcal{N}(7.3, 1.55)$			
	$x_4^{(W)}$	$\mathcal{N}(5.8, 2.55)$			
	$x_5^{(W)}$	$\mathcal{N}(5.78, 2.68)$			
T	$x_1^{(T)}$	$\mathcal{N}(5.7, 2.81)$	$\mathcal{N}(5.45, 1.23)$		
	$x_2^{(T)}$	$\mathcal{N}(4.97, 2.26)$			
	$x_3^{(T)}$	$\mathcal{N}(4.73, 2.15)$			
	$x_4^{(T)}$	$\mathcal{N}(6.47, 2.44)$			

Table 6. Response models from the SWOT analysis for hempcrete.

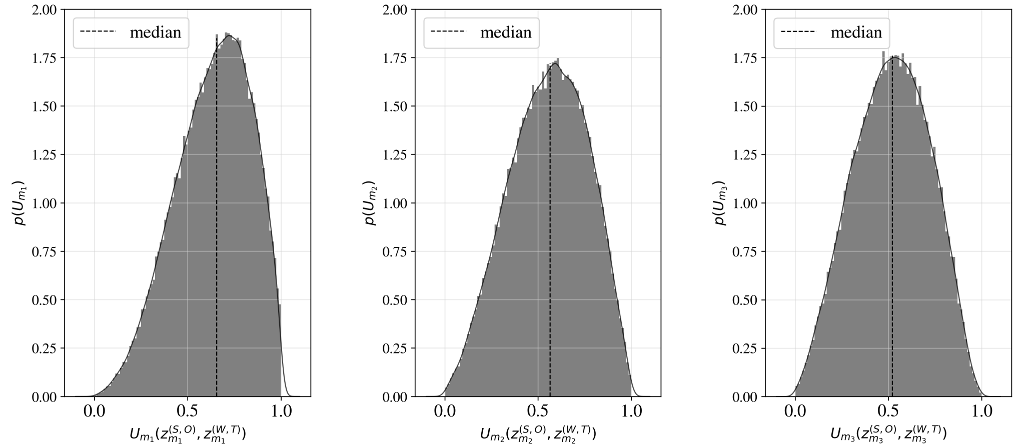
SWOT Factor	SWOT Item	$p(\tilde{x}_{i*}^{(k)})$	$p(\tilde{x}_m^{(k)})$	$\bar{p}(\tilde{z}_m^{(S,O)})$	$\bar{p}(\tilde{z}_m^{(W,T)})$
S	$x_1^{(S)}$	$\mathcal{N}(6.96, 1.22)$	$\mathcal{N}(6.96, 0.83)$	$\mathcal{N}(0.71, 0.095)$	
	$x_2^{(S)}$	$\mathcal{N}(6.78, 1.21)$			
	$x_3^{(S)}$	$\mathcal{N}(7.12, 1.68)$			
O	$x_1^{(O)}$	$\mathcal{N}(5.9, 2.34)$	$\mathcal{N}(6.34, 1.28)$		
	$x_2^{(O)}$	$\mathcal{N}(6.7, 2.6)$			
	$x_3^{(O)}$	$\mathcal{N}(6.5, 1.82)$			
W	$x_1^{(W)}$	$\mathcal{N}(5.88, 1.75)$	$\mathcal{N}(6.28, 0.94)$		$\mathcal{N}(0.35, 0.11)$
	$x_2^{(W)}$	$\mathcal{N}(6.83, 1.11)$			
	$x_3^{(W)}$	$\mathcal{N}(5.03, 2.46)$			
	$x_4^{(W)}$	$\mathcal{N}(7.22, 1.83)$			
T	$x_1^{(T)}$	$\mathcal{N}(6.3, 2.24)$	$\mathcal{N}(6.13, 1.52)$		
	$x_2^{(T)}$	$\mathcal{N}(5.9, 2.05)$			

Table 7. Response models from the SWOT analysis for ferrock.

SWOT Factor	SWOT Item	$p(\tilde{x}_{i*}^{(k)})$	$p(\tilde{x}_m^{(k)})$	$\bar{p}(\tilde{z}_m^{(S,O)})$	$\bar{p}(\tilde{z}_m^{(W,T)})$
S	$x_1^{(S)}$	$\mathcal{N}(6.67, 2.17)$	$\mathcal{N}(6.18, 1.05)$	$\mathcal{N}(0.62, 0.09)$	
	$x_2^{(S)}$	$\mathcal{N}(6.37, 2.22)$			
	$x_3^{(S)}$	$\mathcal{N}(5.85, 2.04)$			
	$x_4^{(S)}$	$\mathcal{N}(5.9, 1.97)$			
O	$x_1^{(O)}$	$\mathcal{N}(5.5, 2.1)$	$\mathcal{N}(5.78, 1.03)$		
	$x_2^{(O)}$	$\mathcal{N}(6.37, 1.73)$			
	$x_3^{(O)}$	$\mathcal{N}(6.06, 2.23)$			
	$x_4^{(O)}$	$\mathcal{N}(5.23, 2.11)$			
W	$x_1^{(W)}$	$\mathcal{N}(6.87, 1.84)$	$\mathcal{N}(6.07, 1.3)$		$\mathcal{N}(0.4, 0.12)$
	$x_2^{(W)}$	$\mathcal{N}(5.13, 2.61)$			
	$x_3^{(W)}$	$\mathcal{N}(6.22, 2.22)$			
T	$x_1^{(T)}$	$\mathcal{N}(5.4, 2.38)$	$\mathcal{N}(5.56, 1.53)$		
	$x_2^{(T)}$	$\mathcal{N}(6.28, 2.69)$			
	$x_3^{(T)}$	$\mathcal{N}(4.8, 2.8)$			

Finally, the normalized probabilistic response models representing the nun-null responses of the experts for the positive $\left(\bar{p}(\tilde{z}_m^{(S,O)})\right)$ and negative $\left(\bar{p}(\tilde{z}_m^{(W,T)})\right)$ SWOT factors are used to obtain samples from the uninorm aggregation function (Equation (21)) through Monte Carlo simulation using 100,000 samples. By doing so, samples of the quantitative scores representing the different candidates eco-materials are obtained. The resulting PDFs of the uninorm aggregation samples are represented in Figure 5 for each eco-material.

In view of the results, rammed earth provides the highest median value (0.655), followed by hempcrete (0.564) and ferrock (0.522). To consider the uncertainty in the assessment, the relationship between the median score ($\bar{U}_m$) over the median absolute deviation of the score ($MAD = median(|\tilde{U}_i - \bar{U}_m|)$, where $\tilde{U}_i$ denotes the samples from the corresponding uninorm aggregation function) is obtained. It can be seen that, for this particular case study, rammed earth provides again the highest score ($\bar{U}_{m_1}/MAD = 4.516$), followed by hempcrete ($\bar{U}_{m_2}/MAD = 3.644$) and ferrock ($\bar{U}_{m_3}/MAD = 3.463$). The larger distance between rammed earth and the other candidates using the median over the MAD score reflects that the respondents not only provide relatively higher scores for rammed earth, but also with less uncertainty.



(**a**) Rammed earth (**b**) Hempcrete (**c**) Ferrock

Figure 5. Probability density function of the simulated results from the uninorm function for different eco-materials. (**a**) m_1 = rammed earth, (**b**) m_2 = hempcrete, (**c**) m_3 = ferrock.

4.3. Practical Implications and Research Limitations

The methodology presented in this paper is generic and can be applied to any group decision-making problem where the input from experts and stakeholders becomes relevant. The incorporation of survey data from a diverse group of experts enables the involvement of multiple perspectives in the decision-making in a rational way. This approach can be very useful in multifaceted industries such as the construction industry, where multiple players with diverse sensitivities are involved. In the specific case of the eco-material selection application presented in this article, the methodology provided has direct practical implications for contractors and designers interested in green and sustainable construction. By using the proposed methodology, they can identify and prioritize candidate eco-materials that align with qualitative (sustainability, aesthetic, etc.) and quantitative (durability, cost, etc.) goals in a structured and data-driven way. Moreover, considering the impact of the selected eco-materials on the United Nations' Sustainable Development Goals (SDGs) has a significant practical implication. It encourages decision-makers to align construction projects with broader global sustainability objectives, making it relevant for policy makers, government agencies, and funding organizations aiming to meet their SDG commitments.

However, the data-driven nature of the proposed methodology becomes also its main limitation. More specifically, the final output is entirely dependent on the quantity and quality of the survey data, and care needs to be taken when designing the data collection process, ensuring the selection of knowledgeable and diverse experts and addressing potential biases in the responses. To mitigate such a limitation, the proposed methodology includes a probabilistic assessment and ranking of eco-material candidate selection, which accounts for variability and uncertainty (e.g., lack of knowledge) in the survey data. This practical aspect is very relevant in dealing with real-world uncertainties in construction projects, enhancing the robustness and rigorousness of the selection decisions.

In summary, the practical implications of this research extend to various stakeholders in the construction industry, including contractors and designers, as well as policy makers and organizations committed to sustainability. The methodology and principles discussed are generic and can easily adapted to other decision-making processes, particularly when dealing with survey data and sustainability criteria.

5. Conclusions

The massive consumption of energy and resources in the construction sector calls for the increasing use of environmentally friendly construction materials, or *eco-materials*. Despite the potential benefits of eco-materials, their adoption in construction projects is hindered by the lack of design codes and the absence of standardized guidelines for rational material selection, among other factors.

This paper introduces a rational and adaptable methodology for large-scale group decision-making in the eco-material selection process. The proposed methodology incorporates input from a diverse panel of experts and stakeholders, encompassing both objective and subjective material attributes, with a special emphasis on the United Nations' Sustainable Development Goals. Novel mixed-behavior aggregation functions are employed to capture the interrelationships between the surveyed data while accounting for the uncertainty in the data.

The methodology was illustrated by applying it to three candidate eco-materials, namely *rammed earth*, *hempcrete*, and *ferrock*. The results demonstrate the effectiveness of the proposed methodology in facilitating rational data-driven decision-making by transforming heterogeneous and subjective inputs into quantitative scores that can be used for material selection and rank with quantified uncertainty. In particular, the methodology is generic and can be easily adapted to different domains by adapting the required SWOT analysis. This practical versatility allows other industries and sectors to adopt the methodology for their decision-making processes, particularly when dealing with survey data and sustainability criteria.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Online Survey

The online survey is carried out with a total of 15 experts, denoted as E_i, which includes engineering academics (A) and engineering practitioners (P) from various countries. The categorical classification of these experts (E_i, where $i = 1, \ldots, 15$) is presented in Table A1. Tables A2–Table A4 provide an overview of the responses provided by these experts for the SWOT items as outlined in Table 2–Table 4, respectively.

Table A1. Categories of the experts. A: academic engineers, P: practitioner engineers.

Expert	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}	E_{13}	E_{14}	E_{15}
Category	P	P	P	A	A	A	P	A	A	A	A	P	A	P	P

Table A2. Online survey for rammed earth. Graded from x_{min} = 1 (“not relevant”) to x_{max} = 9 (“completely relevant”); 0 denotes “unsure”.

Rammed Earth SWOT Factor	SWOT Item	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}	E_{13}	E_{14}	E_{15}
S	$x_1^{(S)}$	9	6	9	9	9	8	8	9	0	7	5	7	2	9	6
	$x_2^{(S)}$	6	5	0	5	9	5	9	7	3	6	9	8	2	9	6
	$x_3^{(S)}$	7	7	0	8	9	6	8	7	5	7	5	7	6	9	8
	$x_4^{(S)}$	9	7	0	7	9	0	9	9	8	8	7	7	6	9	6
W	$x_1^{(W)}$	6	8	0	7	3	7	6	8	2	9	8	7	8	5	8
	$x_2^{(W)}$	6	4	0	8	3	8	8	9	7	8	6	8	9	2	8
	$x_3^{(W)}$	6	6	0	6	0	7	4	9	9	8	6	7	9	8	8
	$x_4^{(W)}$	6	5	0	6	3	8	6	9	4	5	2	7	9	1	8
	$x_5^{(W)}$	6	7	0	8	5	6	7	9	2	7	5	2	9	1	6
O	$x_1^{(O)}$	8	7	9	8	8	8	2	9	4	9	7	6	7	9	8
	$x_2^{(O)}$	8	3	7	9	7	6	9	9	4	5	6	6	8	9	6
T	$x_1^{(T)}$	6	2	0	8	1	9	6	5	6	8	2	4	9	0	6
	$x_2^{(T)}$	6	3	0	6	1	8	2	3	6	5	5	4	8	5	7
	$x_3^{(T)}$	2	4	0	4	0	5	3	3	6	6	7	0	8	1	6
	$x_4^{(T)}$	6	8	0	7	0	7	3	9	8	7	3	0	8	1	7

Table A3. Online survey for hempcrete. Graded from x_{min} = 1 (“not relevant”) to x_{max} = 9 (“completely relevant”); 0 denotes “unsure”.

Hempcrete SWOT Factor	SWOT Item	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}	E_{13}	E_{14}	E_{15}
S	$x_1^{(S)}$	7	4	0	7	8	7	8	8	0	0	8	6	0	7	6
	$x_2^{(S)}$	7	5	0	8	8	0	8	0	0	6	5	7	6	8	6
	$x_3^{(S)}$	7	2	0	8	8	7	8	8	0	7	5	7	8	9	7
W	$x_1^{(W)}$	6	7	0	7	7	7	3	0	5	5	3	7	8	3	6
	$x_2^{(W)}$	6	5	0	7	8	0	8	0	7	0	6	0	8	6	6
	$x_3^{(W)}$	6	3	0	8	1	0	3	0	6	8	3	5	0	5	6
	$x_4^{(W)}$	6	7	0	9	9	8	4	9	7	8	4	8	8	4	6
O	$x_1^{(O)}$	7	5	0	7	7	1	7	0	6	8	3	6	0	9	5
	$x_2^{(O)}$	8	5	0	8	9	1	8	0	0	6	8	7	0	9	6
	$x_3^{(O)}$	8	6	0	8	5	7	6	8	6	7	1	6	7	9	6
T	$x_1^{(T)}$	6	7	0	9	5	7	5	0	0	7	9	7	0	1	5
	$x_2^{(T)}$	6	4	0	6	0	0	7	0	7	8	5	7	0	1	6

Table A4. Online survey for ferrock. Graded from x_{min} = 1 ("not relevant") to x_{max} = 9 ("completely relevant"); 0 denotes "unsure".

Ferrock SWOT Factor	**SWOT Item**	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}	E_{13}	E_{14}	E_{15}
S	$x_1^{(S)}$	1	4	8	8	0	0	8	8	0	8	0	7	7	6	6
	$x_2^{(S)}$	1	3	5	7	8	0	7	8	0	5	0	8	7	8	7
	$x_3^{(S)}$	2	5	6	7	2	0	7	8	6	5	0	8	7	6	6
	$x_4^{(S)}$	2	3	3	6	0	0	6	8	6	8	0	6	7	6	7
W	$x_1^{(W)}$	2	7	7	8	0	0	5	9	7	7	8	0	8	6	6
	$x_2^{(W)}$	1	4	8	8	3	0	1	0	5	5	0	8	7	3	6
	$x_3^{(W)}$	1	5	9	7	7	7	4	0	0	8	0	0	5	8	6
O	$x_1^{(O)}$	2	6	7	7	7	0	3	0	7	5	0	7	2	5	7
	$x_2^{(O)}$	2	5	5	7	0	0	6	8	6	0	0	7	8	7	7
	$x_3^{(O)}$	2	5	0	8	7	0	7	8	7	7	0	7	2	4	7
	$x_4^{(O)}$	2	5	6	7	4	0	3	0	8	6	0	6	2	7	6
T	$x_1^{(T)}$	1	3	4	6	8	0	5	0	7	7	0	6	2	8	6
	$x_2^{(T)}$	1	8	3	9	4	0	6	2	8	8	8	7	8	8	7
	$x_3^{(T)}$	1	2	3	6	0	0	3	0	4	9	0	7	2	7	7

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