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Gray Multi-Criteria Decision-Making Model for Optimization of Cost for Sustainable Design and Construction Using Value Engineering

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Abstract
This research aims to optimize of sustainable design and construction cost using gray multi-criteria decision-making through value engineering approach by reducing unnecessary costs while maintaining essential functionality. Despite its advantages, this approach has not been widely explored in sustainable design and construction due to several constraints such as an excessive focus on cost, inability to meet varied criteria, reliance on team votes for solution ranking, disregard for inherent uncertainties, and disputes among team members. These limitations have hindered its effectiveness. To tackle these challenges, this research endeavors to create a comprehensive model that combines value engineering with sustainable design and construction cost management, utilizing gray multi-criteria decision-making. The model comprises two phases. The first phase involves identifying an initial set of improvement solutions and localizing criteria extracted from the literature through the perspectives of the value engineering team. These criteria are then weighted using the gray stepwise weight assessment ratio analysis technique. Subsequently, the team assigns scores to each solution based on the criteria list using gray numbers. The scores are amalgamated using the gray evaluation based on distance from average solution method, and the solutions are prioritized accordingly. By employing this method, the study aims to overcome the limitations of conventional value engineering and establish a more efficient framework for sustainable design and construction cost management.

Keywords
Gray Method, Cost Optimization, Sustainable design and Construction, Value Engineering

1. Introduction
Value engineering (VE) helps designers choose materials by balancing quality and cost, including Life Cycle Cost (LCC). VE is a method used within Multi-Criteria Decision-Making (MCDM), a field that encompasses various approaches and strategies aimed at refining decision-making processes across multiple criteria. MCDM techniques simplify the evaluation and comparison of options based on diverse factors, aligning judgments with specific goals and preferences. VE stands out for its ability to consider project functions and requirements to achieve sustainable design and construction at an optimal cost. Recent studies have increasingly focused on the application of VE in the design and construction industry (Ekanayake et al., 2019; Karunasena & Gamage, 2017; Kissi et al., 2017; Lee, 2018; Nasir et al., 2016; Tanko et al., 2018). Many of these investigations aim to enhance building sustainability ratings (Latief et al., 2017; Li et al., 2019; Yu et al., 2018). Achieving sustainable design and construction standards often necessitates linking these goals to international standard tests for objective evaluations. These standards assess the degree of sustainability achieved and compliance with LEED requirements. Such evaluations can range from minimal acceptable standards to higher benchmarks, helping to use material quality effectively within VE methods and promoting the application of VE in sustainable design and construction. For instance, sustainable energy-saving principles have been employed to create judgment models through VE aimed at optimizing green building designs, as illustrated by Usman et al. (2018) and Yasser et al. (2023). Conversely, the rise of global and intensely competitive markets has made it crucial for businesses to

offer valuable products to customers at the lowest possible prices and costs, as this is a key factor in achieving competitive success (Tohidi, 2011). Consequently, organizations have integrated both performance and cost metrics into their strategies for gaining a competitive edge (Ibusuki & Kaminski, 2007). As a result, numerous techniques for cost management have been introduced, with value engineering being one of the most effective, having been established by Lawrence Miles in 1940 (Annappa & Panditrao, 2012; Shen & Yu, 2012). Value engineering is defined as “an organized approach to efficiently. Evaluating final solutions in the value engineering process, as well as other multi-criteria decision-making (MCDM) challenges, often involves uncertain information, which can make assessments difficult for decision-makers (DMs). In many real-life scenarios, the preferences for various alternatives and the importance of criteria are not always clearly defined. In such cases, traditional MCDM approaches that rely on exact values may not yield satisfactory results (Stanujkic et al., 2017; Keshavarz Ghorabaee et al., 2018). Factors such as limited access to comprehensive information (inadequate data for decision-making), the reliance on qualitative data, and differing opinions among experts often necessitate the use of linguistic variables in the decision-making process. Consequently, it is essential for the value engineering process to employ methods that address the ambiguity and uncertainty inherent in these decisions. This study aims to introduce a model that leverages value engineering for cost management in sustainable design and construction, utilizing gray number theory and integrating two MCDM techniques: Stepwise Weight Assessment Ratio Analysis (SWARA) and Evaluation based on Distance from Average Solution (EDAS). Gray system theory is suggested as a solution for dealing with ambiguous situations, particularly when information is insufficient or inaccurate (Stanujkic et al., 2017; Keshavarz Ghorabaee et al., 2018).

2. Literature Review

The value engineering (VE) is widely recognized as a structured approach to improving value by reducing unnecessary costs while maintaining essential functions (Latief et al., 2017). However, traditional VE applications in design and construction and supply chain management often overemphasize cost at the expense of other sustainability criteria and struggle with uncertainty and subjective judgments among team members. Integrating gray multi-criteria decision-making (MCDM) methods addresses these limitations by incorporating uncertainty and enabling more robust prioritization of cost reduction solutions (Ho et al., 2010). For example, the use of gray SWARA and EDAS methods allows for the aggregation of expert opinions and the prioritization of solutions under uncertain conditions, leading to stable and reliable decision outcomes in real-world case studies, such as power plant projects (Kabir et al. 2014). Since the year 2000, Multi-Criteria Decision Making (MCDM) has become a widely used research tool for addressing complex issues and enhancing decision-making processes across various sectors. One notable application of MCDM is in material selection (Eltarabishi et al., 2020). When determining the best alternative for building design, it is crucial to carefully assess multiple options (Brauers et al., 2010). Researchers have explored material selection from various angles, considering factors such as cost and sustainability (Onochie et al., 2017). Conversely, studies by (Al et al. 2014) has focused on assessing materials based on quality, performance, durability, and expense. A systematic review by (Kabir et al. 2014) provided an in-depth analysis of the use of MCDM methods in the selection of sustainable materials. The integration of gray MCDM models with value engineering is particularly relevant for sustainable design and construction, where cost optimization must be balanced with environmental and social objectives. For instance, gray-based models have been applied to optimize life cycle energy and cost in building projects, demonstrating significant energy savings and rapid investment payback periods. Similarly, gray theory-enhanced neural network models have improved the accuracy and efficiency of design and construction cost estimation, reducing errors and supporting more sustainable investment decisions (Ghorabaee et al., 2018). With the growing focus on sustainability, assessing the environmental impact of design and construction is now crucial (Xiang et al., 2021). This assessment includes considerations like carbon footprint, recyclability, energy usage during production, and the exhaustion of natural resources. Choosing eco-friendly materials supports green building practices and helps minimize the ecological footprint. Numerous studies have explored sustainable design and construction through value engineering to optimize costs. Various approaches, including Multi-Criteria Decision Making (MCDM), case studies, analytical methods, numerical analyses, and statistical techniques, have been implemented to meet the goals of these studies. This research dives into gray numbers, unraveling their significance and application. In the next section, SWARA-Gray and EDAS-Gray methods, shedding light on how they come to life in practical scenarios.

3. Gray Method

Gray system theory serves as a powerful method for addressing problems characterized by partial information and uncertainty through mathematical analysis (Stanujkic et al., 2017). Initially developed by Deng in 1982, this theory merges principles from system theory, space theory, and control theory (Pan et al., 2019). It proves particularly effective in the following scenarios (Wu, 2006):

- When dealing with incomplete or insufficient information.
- To overcome limitations associated with statistical methods.
- In estimating the behavior of uncertain systems with restricted or minimal data.

3.1 Gray Numbers

The grey method GM (1, 1) is a widely utilized grey forecasting model that necessitates a minimum of four observations. The first step involves applying an accumulating generation operator (AGO) to the data. Next, the governing differential equation of the model is solved to derive the predicted value for the system. The original data's predicted values are then obtained using the inverse accumulating generation operator (IAGO). The conventional process for modeling with GM (1, 1) is outlined below:

Assume that $X^{(0)} = (x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n))$ is a nonnegative sequence, where $x^{(0)}(k) \geq 0, k = 1,2, \ldots, n$. Then, $X^{(1)} = (x^{(1)}(1), x^{(1)}(2), \ldots, x^{(1)}(n))$ is called the 1-AGO (Accumulating Generation Operator) sequence of $X^{(0)}$, where

$$x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(k), \quad k = 1, 2, \ldots, n, \qquad (1)$$

and $Z^{(1)} = (z^{(1)}(2), z^{(1)}(3), \ldots, z^{(1)}(n))$ is called the mean generation of consecutive neighbors sequence of $X^{(1)}$, where

$$z^{(1)}(k) = 0.5 \times \left(x^{(1)}(k) + x^{(1)}(k-1)\right), \quad k = 2, 3, \ldots, n. \qquad (2)$$

Definition 2. (See [1]). Let $X^{(0)}$, $X^{(1)}$, and $Z^{(1)}$ be the same as in Definition 1; then,

$$x^{(0)}(k) + az^{(1)}(k) = b, \qquad (3)$$

is called the basic form of GM(1,1), which is derived from Figure 1, that is,

$$b - a \cdot \text{MEAN} = x^{(0)}(k) \Longrightarrow b - az^{(1)}(k) = x^{(0)}(k) \Longrightarrow x^{(0)}(k) + az^{(1)}(k) = b. \qquad (4)$$

Let X(0), X(1), and Z(1) be the same as in Definition 1, $\hat{a} = (a, b)^T$ be a sequence of parameters, and

$$Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix}, \qquad B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(n) & 1 \end{bmatrix}. \qquad (5)$$

Then, the least square estimate sequence of grey differential equation x(0)(k) + az(1)(k) = b satisfies

$$\hat{a} = \left(B^T B\right)^{-1} B^T Y. \qquad (6)$$

3.2 SWARA-Gray method

Weighting criteria stands as a pivotal element in the realm of MCDM (Multiple Criteria Decision Making) challenges. It's truly fascinating how experts step into this intricate web, playing a crucial role in assessing both the criteria and their corresponding weights. Their insights become indispensable in shaping the decision-making journey. Enter the SWARA method, a fresh innovation that emerged from the minds of Kersuliene and colleagues in 2010. This approach empowers decision-makers to not just choose and assess criteria but also to deftly assign weights to them. What sets SWARA apart? It boasts user-friendliness, simplicity, and a remarkable efficiency that slashes the time investment required for implementation. This makes it an appealing choice for those navigating the often complex landscapes of decision-making (Hashemkhani Zolfani et al., 2013; Hashemkhani Zolfani & Saparauskas, 2013; Valipour et al., 2018).

The key steps for determining weights using the SWARA-Gray method are outlined as follows (Mavi et al., 2018):

Step 1: Rank the Criteria

The criteria identified by the experts are first ranked based on their importance. The most crucial criterion is assigned the highest rank (first), while the least important one receives the lowest rank (last).

Step 2: Assess the Relative Importance of Each Criterion (Sj)

In this step, the relative importance of each criterion, denoted as SjS _jSj, is determined in comparison to the more important criteria. The importance of each criterion is evaluated relative to those ranked higher.

Step 3: Compute the Coefficient KjK_jKj
The coefficient KjK_jKj, which is derived from the relative importance of each criterion, is calculated using Equation (7).

$$K_j = \begin{cases} [1,1];\ j=1 \\ S_j + [1,1];\ j>1 \end{cases}. \qquad \text{.......... (7)}$$

Step 4: Compute the Initial Weight for Each Criterion
The initial weights for the criteria are calculated using Equation (8). It's important to note that the weight of the first criterion, which holds the highest importance, is set to 1.

$$q_j = \begin{cases} [1,1];\ j=1 \\ \dfrac{q_{j-1}}{K_j};\ j>1 \end{cases}. \qquad \text{..................... (8)}$$

Step 5: Calculate the Final Normalized Weight
In the final step of the SWARA method, the normalized weights of the criteria are determined using Equation (9). These represent the final weights for each criterion.

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j}, \qquad \text{....................... (9)}$$

w_j is represented as a gray number in the form w_j=[w_j−;w_j+]w j _ = \left[w j _ ^- ; w j _ ^+ \right]w_j=[w_j−;w_j+], where w_j−w_j^-w_j− is the lower limit and w_j+w j _^+w_j+ is the upper limit of the weight for criterion j.

3.3 EDAS-Gray method

The computational approach of the EDAS method is highly innovative, drawing on established techniques from well-known multi-criteria decision-making (MCDM) methods, such as Simple Additive Weighting (SAW) (Kaliszewski & Podkopaev, 2016), TOPSIS (Yoon & Hwang, 1995), and VIKOR (Opricovic, 1998). The EDAS method is anticipated to become a widely used tool for addressing various MCDM problems in the near future (Stanujkic et al., 2017). Numerous studies have already applied this method, either in its traditional form or adapted variants, across different fields (Stević et al., 2019). One of the key advantages of the EDAS method is its ability to handle inconsistent criteria without the need to calculate ideal and anti-ideal solutions (Keshavarz et al., 2018).

The steps of the EDAS-Gray method in a decision-making problem with mmm alternatives and nnn criteria are outlined as follows (Stanujkic et al., 2017).

Step 1: The gray decision matrix is constructed using Equation (10).

$$X = \begin{bmatrix} [\underline{x}_{11}, \overline{x}_{11}] & [\underline{x}_{12}, \overline{x}_{12}] & \cdots & [\underline{x}_{1n}, \overline{x}_{1n}] \\ [\underline{x}_{21}, \overline{x}_{21}] & [\underline{x}_{22}, \overline{x}_{22}] & \cdots & [\underline{x}_{2n}, \overline{x}_{2n}] \\ \vdots & \vdots & \vdots & \vdots \\ [\underline{x}_{m1}, \overline{x}_{m1}] & [\underline{x}_{m2}, \overline{x}_{m2}] & \cdots & [\underline{x}_{mn}, \overline{x}_{mn}] \end{bmatrix}. \qquad \text{.......... (10)}$$

Step 2: The gray mean solution for all criteria is calculated using Equations (11)–(13).

$$x_j^* = \left([\underline{x}_1^*, \overline{x}_1^*]\right), \left([\underline{x}_2^*, \overline{x}_2^*]\right), \left([\underline{x}_n^*, \overline{x}_n^*]\right); \qquad \text{................. (11)}$$

$$\underline{x}_j^* = \frac{\sum_{i=1}^{m} \underline{x}_{ij}}{m}; \qquad \text{... (12)}$$

$$\overline{x}_j^* = \frac{\sum_{i=1}^{m} \overline{x}_{ij}}{m}. \qquad \text{... (13)}$$

Step 3: The Positive Distance from Average (PDA) and Negative Distance from Average (NDA) matrices are calculated as gray numbers, considering both profit and cost criteria, using Equations (14)–(17).

$$\underline{d_{ij}^{+}} = \begin{cases} \dfrac{\max\left(0, \left(\underline{x_{ij}} - \overline{x_j^*}\right)\right)}{0.5\left(\underline{x_j^*} + \overline{x_j^*}\right)} ; j \in \Omega_{\max} \\ \dfrac{\max\left(0, \left(\underline{x_j^*} - \overline{x_{ij}}\right)\right)}{0.5\left(\underline{x_j^*} + \overline{x_j^*}\right)} ; j \in \Omega_{\min} \end{cases} ; \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

$$\overline{d_{ij}^{+}} = \begin{cases} \dfrac{\max\left(0, \left(\overline{x_{ij}} - \underline{x_j^*}\right)\right)}{0.5\left(\underline{x_j^*} + \overline{x_j^*}\right)} ; j \in \Omega_{\max} \\ \dfrac{\max\left(0, \left(\overline{x_j^*} - \underline{x_{ij}}\right)\right)}{0.5\left(\underline{x_j^*} + \overline{x_j^*}\right)} ; j \in \Omega_{\min} \end{cases} ; \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

$$\underline{d_{ij}^{-}} = \begin{cases} \dfrac{\max\left(0, \left(\underline{x_j^*} - \overline{x_{ij}}\right)\right)}{0.5\left(\underline{x_j^*} + \overline{x_j^*}\right)} ; j \in \Omega_{\max} \\ \dfrac{\max\left(0, \left(\underline{x_{ij}} - \overline{x_j^*}\right)\right)}{0.5\left(\underline{x_j^*} + \overline{x_j^*}\right)} ; j \in \Omega_{\min} \end{cases} ; \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

$$\overline{d_{ij}^{-}} = \begin{cases} \dfrac{\max\left(0, \left(\overline{x_j^*} - \underline{x_{ij}}\right)\right)}{0.5\left(\underline{x_j^*} + \overline{x_j^*}\right)} ; j \in \Omega_{\max} \\ \dfrac{\max\left(0, \left(\overline{x_{ij}} - \underline{x_j^*}\right)\right)}{0.5\left(\underline{x_j^*} + \overline{x_j^*}\right)} ; j \in \Omega_{\min} \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots.. (17)$$

Step 4: The weighted sum of the positive and negative gray distances from the average for all alternatives is calculated using Equations (18)–(21).

$$\underline{Q_i^{+}} = \sum_{j=1}^{n} \underline{w_j d_{ij}^{+}} ; \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

$$\overline{Q_i^{+}} = \sum_{j=1}^{n} \overline{w_j}\,\overline{d_{ij}^{+}} ; \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

$$\underline{Q_i^{-}} = \sum_{j=1}^{n} \underline{w_j d_{ij}^{-}} ; \text{ and} \quad \ldots\ldots\ldots\ldots\ldots\ldots (20)$$

$$\overline{Q_i^{-}} = \sum_{j=1}^{n} \overline{w_j}\,\overline{d_{ij}^{-}} . \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

Step 5: The weighted sum of the gray PDA and the weighted sum of the gray values for each alternative are normalized using Equations (22)–(25).

$$\underline{S_i^+} = \frac{\underline{Q_i^+}}{\max_k \overline{Q_k^+}} ; \quad \ldots\ldots\ldots\ldots\ldots.. (22)$$

$$\overline{S_i^+} = \frac{\overline{Q_i^+}}{\max_k \overline{Q_k^+}} ; \quad \ldots\ldots\ldots\ldots.. (23)$$

$$\underline{S_i^-} = 1 - \frac{\underline{Q_i^-}}{\max_k \overline{Q_k^+}} \text{ and} \quad \ldots\ldots\ldots\ldots... (24)$$

$$\overline{S_i^-} = 1 - \frac{\overline{Q_i^-}}{\max_k \overline{Q_k^+}}. \quad \ldots\ldots\ldots\ldots..\ldots (25)$$

Step 6: The appraisal score (SiS_iSi) for all alternatives is calculated using Equations (26) and (27).

$$S_i = \frac{1}{4}\left(\underline{S_i^+} + \overline{S_i^+} + \underline{S_i^-} + \overline{S_i^-}\right) \text{, or} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots... (26)$$

$$S_i = \frac{1}{2}\left[(1-\alpha)\left(\underline{S_i^-} + \underline{S_i^+}\right) + \alpha\left(\overline{S_i^-} + \overline{S_i^+}\right)\right]. \quad \ldots\ldots\ldots\ldots.. (27)$$

If decision-makers wish to assign different weights to the lower or upper bounds of the gray interval, or if they want to conduct a sensitivity analysis, they can use parameter aaa.

Step 7: The alternatives are ranked based on their appraisal scores. The alternative with the highest SiS_iSi value is considered the best alternative.

4. Methodology

According to the literature, value engineering studies are carried out in three stages: pre-workshop, workshop, and post-workshop (Lin et al., 2011). This approach is implemented through six phases, which include information gathering, performance analysis, creativity, evaluation, development, and presentation at the organizational level (Zarandi et al., 2011; El-Nashar, 2017). In this research, we have restructured this model to attain the optimal cost for sustainable design and construction. The steps involved in this study are depicted in Figure 1.

4.1 Input data

At the outset, following the collection of baseline data and the establishment of scope and objectives, a value engineering team was assembled. This team consisted of value engineering consultants and sustainable design and construction experts who possess the requisite experience and knowledge in the field. Their role is to identify, assess, and address value-related issues, develop solutions, and create a decision-making framework, including criteria and evaluation scores. The team leader oversees the study team through various phases of the process. The initial criteria list is derived from a review of relevant literature. Subsequently, we refine the model by gathering insights from the value engineering team using the Fuzzy method.

4.2 Processing

During the study of the value engineering process, the project team reviewed and analyzed the information gathered in the study phase and created a Function Analysis System Technique (FAST) diagram for the project. Using this FAST diagram as a foundation, team members brainstormed ideas employing creative techniques. However, not all proposals were feasible; therefore, the initial ideas were assessed by experts from the value engineering team to compile a list of potential cost reduction solutions. Subsequently, the team undertook the following steps to evaluate and rank these solutions. They assessed the value of each solution based on criteria established in the earlier stage and developed a decision matrix. The significance of these criteria was determined using the SWARA-Gray method, while the EDAS-Gray method was applied to rank the identified solutions and select the optimal option.

4.3 Output findings

In the final stage, the previous findings were made available to the final decision-makers (senior executives of the company who have an experience in sustainable design and construction), and executive suggestions were made to achieve the planned goals.

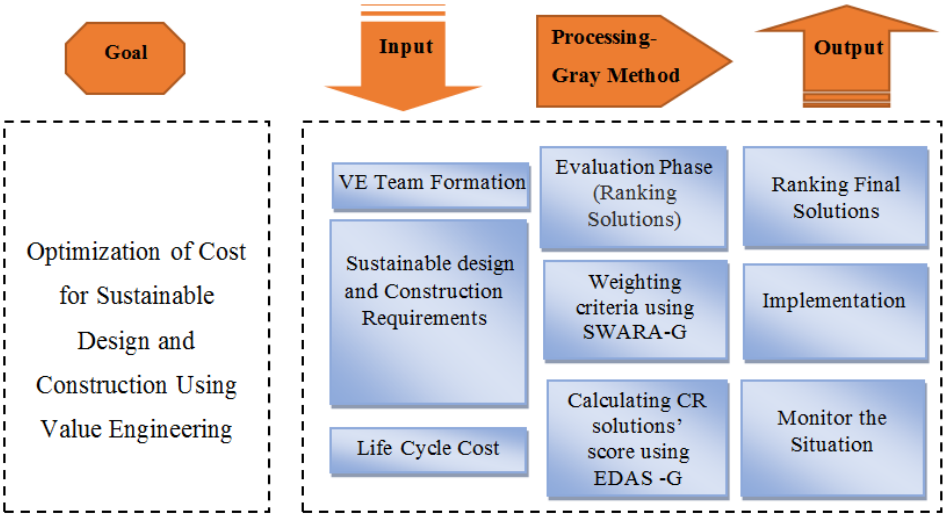

Fig. 1 Research flowchart

5. Data Analysis and Model Results

The value engineering literature highlights that the project team is responsible for identifying, evaluating, and resolving value-related problems and challenges, developing alternative solutions, and establishing a decision-making framework, including criteria and assessment scores. The value team leader guides the team through each phase of the process, ensures coordination among members, and consolidates their inputs. According to established standards, value engineering is typically conducted in three main stages. In the first stage (pre-study), relevant data is collected, the foundation and scope of the study are defined, and the project team is assembled. The second stage (study phase) involves conducting workshops focused on creativity and idea generation, preliminary evaluation, idea refinement, and the formulation of a list of potential solutions. In the third stage (post-study), key activities include analyzing the results, proposing performance improvement strategies, and overseeing the implementation and evaluation of outcomes. During the evaluation phase, many of the initially proposed solutions were discarded due to issues such as redundancy, limited feasibility, lack of consensus, misalignment with the project scope, vagueness, or potential negative impacts on project objectives. After thorough evaluation, refinement, and development of the initial ideas, ten final solutions were selected based on literature review to support cost optimization in sustainable design and construction. These ten selected solutions are presented in Table 1.

Table 1 Value Engineering Factors to Optimize the Cost for Sustainable Design and Construction

Code	VE Factor	Description	References
VE.1	Function-Oriented Design	Focus on the essential functions of building components to eliminate or reconfigure non-critical elements, reducing material and energy use.	Keshavarz Ghorabaee et al. (2015)
VE.2	Life Cycle Cost Analysis (LCCA)	Evaluate total costs over the asset's lifespan, including operation, maintenance, and end-of-life, not just initial costs.	Zavadskas et al. (2019); Sarmah et al. (2024)
VE.3	Sustainable Material Selection	Use eco-friendly, low-embodied energy, and locally available materials to reduce both cost and environmental impact.	Stević et al. (2019)
VE.4	Design Simplification and Modularity	Promote standardized or modular construction systems to reduce complexity, shorten timelines, and lower costs.	Davies et al. (2025); Multiproject (2023)
VE.5	Energy Efficiency Integration	Incorporate passive design strategies, renewable energy systems, and efficient MEP systems early in design.	Li et al. (2020); U.S. DOE (2022)
VE.6	Early Stakeholder Involvement	Engage clients, engineers, and contractors early in the design phase to align sustainability goals with cost-saving opportunities.	Stanujkic et al. (2017); Alsyed Construction (2023)
VE.7	Lean Construction Practices	Apply lean principles to minimize waste, optimize processes, and improve value delivery.	Opricovic (1998); Kaliszewski & Podkopaev (2016)
VE.8	Phased Construction Strategy	Implement phased or incremental project delivery to improve budget management and reduce risk.	Karabasevic et al. (2018); Zhang et al. (2019)
VE.9	Adaptability and Flexibility in Design	Design buildings that are adaptable to future changes in use, which reduces the need for expensive retrofits.	Zavadskas et al. (2019); ISO 20887:2020
VE.10	Performance-Based Evaluation Metrics	Use measurable sustainability benchmarks (e.g., LEED, BREEAM) to evaluate value options, ensuring environmental and economic performance.	Bielinskas et al. (2018); Stević et al. (2019)

The prioritizing solutions require identifying criteria based on sustainable design and construction requirements. The gray process has been used for this purpose. Table 2 shows the final list of the requirements for sustainable design and construction.

Table 2 List of Sustainable Design and Construction Factors

Group	Code	Sustainable Factors	References
Sustainable design (SD)	SD.1	Apply value engineering requirements during the early stage of sustainable design.	Fewings et al. (2019)
	SD.2	Providing alternatives and suggestions for sustainable design to achieve optimal project cost.	Reddy et al. (2016); Gunarathne et al. (2022)
	SD.3	Applying LEED and design requirements and their impact on cost and value engineering requirements.	Araújo et al. (2020); Li et al. (2022)
	SD.4	Efficiency of the planning and design team, sustainability requirements and value engineering.	Araújo et al. (2020); Bamgbade et al. (2019)
	SD.5	Cost analysis during the project planning stage.	Bamgbade et al. (2019)
Sustainable construction (SC)	SC.1	Reduce the construction materials emissions.	Naji et al. (2022)
	SC.2	Renewable and clean energy sources use.	Zainul et al. (2005)
	SC.3	Monitoring water consumption performance.	Nagapan et al. (2011)
	SC.4	Prepare a plan for waste management of construction and demolition.	Naji et al. (2022)
	SC.5	Continual communication between management and workers and correcting unsafe practices.	Lavi (2024)

In the subsequent phase, the weights of the evaluation criteria were determined using the SWARA-Gray method. Initially, value engineering experts were asked to evaluate the relative importance of the main criteria. The results of this ranking process are presented in the first column of Table 3. Consensus was reached among all experts regarding both the order and the relative importance of the criteria. The second to fourth columns of Table 3 display the outcomes of Steps 2 to 4 of the SWARA-Gray method, respectively. The final step, involving the normalization of the weights using Equation (9), is reflected in the fifth column of the same table. In a similar manner, the SWARA-Gray method was also applied to determine the weights of sub-criteria under the categories of performance, feasibility, applicability, effectiveness, and compliance with environmental requirements. These results are summarized in Table 4.

Table 3 Main Group Weight

Group	Comparative importance of average value (S_j)		Coefficient $k_j = S_j + [1; 1]$		Recalculated weight q_j		Local weight w_j	
SD	0.170	0.213	0.196	0.255	0.196	0.213	0.170	0.196
SC	0.207	0.253	0.242	0.322	0.242	0.253	0.207	0.242

Table 4 Capability of Sustainable Factors

Sustainable Factors	Comparative importance (Sj)		Coefficient kj = Sj + [1; 1]		Recalculated weight qj		Local weight wj		Final weight	
Sustainable design (SD)										
SD.1	0.168	0.180	0.286	0.425	0.671	0.336	0.593	0.613	0.168	0.180
SD.2	0.250	0.220	0.408	0.456	0.582	0.456	0.632	0.687	0.250	0.220
SD.3	0.230	0.210	0.378	0.221	0.325	0.778	0.455	0.483	0.230	0.210
SD.4	0.300	0.280	0.518	0.456	0.582	0.456	0.632	0.687	0.300	0.280
SD.5	0.230	0.210	0.378	0.345	0.436	0.345	0.440	0.511	0.230	0.210
Sustainable construction (SC)										
SC.1	0.250	0.220	0.408	0.365	0.358	0.987	0.503	0.523	0.250	0.220
SC.2	0.200	0.180	0.318	0.657	0.768	0.657	0.566	0.604	0.200	0.180
SC.3	0.230	0.210	0.378	0.563	0.632	0.563	0.347	0.386	0.230	0.210
SC.4	0.320	0.290	0.548	0.351	0.431	0.354	0.486	0.865	0.320	0.290
SC.5	0.657	0.351	0.745	0.644	0.987	0.116	0.678	0.987	0.657	0.351

To prioritize the identified solutions, the value engineering team experts were asked to assess each alternative against the sub-criteria using linguistic variables, as defined in Table 5. Through collaborative discussions, the experts evaluated the performance of each solution with respect to the final criteria and reached a consensus to construct the decision matrix. The outcome of this evaluation process is presented in Table 6.

Next, the linguistic variables in Table 6 were converted into gray numbers using the scale provided in Table 5, resulting in the final decision matrix expressed in gray numbers. Following this, the gray average solution was calculated using Equations (12) and (13). Based on the type of each criterion, the Positive Distance from Average (PDA) and Negative Distance from Average (NDA) matrices were then derived using Equations (14) to (17).

Table 5 Linguistic variables corresponding to gray numbers (Turskis & Zavadskas, 2010)

Linguistic Variable	Gray Number Range [a−,a+][a^-, a^+]
Very Low (VL)	[0.0, 0.1]
Low (L)	[0.1, 0.3]
Medium-Low (ML)	[0.2, 0.4]
Medium (M)	[0.4, 0.6]
Medium-High (MH)	[0.6, 0.8]
High (H)	[0.7, 0.9]
Very High (VH)	[0.9, 1.0]

Table 6 Final Decision Matrix Assessed Using Linguistic Variables Expressed as Gray Numbers

Sustainable Factors	SD.1	SD.2	SD.3	SD.4	SD.5	SC.1	SC.2	SC.3	SC.4	SC.5
VE.1	0.85	1.00	0.75	1.00	0.75	0.50	0.80	0.60	0.70	0.75
VE.2	1.00	1.00	1.00	0.70	1.00	0.60	0.80	0.65	0.60	0.70
VE.3	0.70	1.00	0.60	0.80	0.85	1.00	0.70	0.75	0.80	0.75
VE.4	0.65	0.60	0.70	0.65	0.60	0.80	0.75	0.70	1.00	0.55
VE.5	0.90	0.85	0.80	0.75	0.80	0.65	1.00	0.75	0.65	0.80
VE.6	1.00	0.60	0.55	1.00	0.70	0.75	0.80	0.75	0.65	0.60
VE.7	0.65	0.70	0.75	1.00	0.55	0.80	0.70	0.60	0.75	1.00
VE.8	0.60	0.55	0.65	1.00	0.70	0.50	0.60	0.55	0.60	0.55
VE.9	0.75	0.80	1.00	0.90	0.85	0.60	0.75	0.70	0.80	0.85
VE.10	0.80	0.90	0.50	0.85	0.65	0.40	0.75	1.00	0.60	0.65

In the following step, the weighted and normalized gray sums of the positive and negative distances from the average were calculated using Equations (18) to (25). These results are presented in Table 7. Subsequently, the estimated score (SiS_iSi) for each alternative was computed using Equation (26). These results represent the outcome of the prioritization process using the EDAS-Gray method.

Table 7 The weighted and the normalized weighted grey sums of positive and negatives distances from the average

VE Factor	Si −	Rank Si −	Si +	Rank Si +	Qi −	Rank Qi −	Qi +	Rank Qi +
VE.1	0.4	5	0.8	2	0.2	6	0.9	1
VE.2	0.6	3	0.7	3	0.4	5	0.7	2
VE.3	0.5	4	0.9	1	0.3	4	0.8	3
VE.4	0.7	2	0.6	4	0.1	7	0.6	4
VE.5	0.8	1	0.5	5	0.2	6	0.7	2
VE.6	0.3	7	0.6	4	0.5	3	0.7	2
VE.7	0.4	5	0.7	3	0.4	5	0.5	6
VE.8	0.5	4	0.9	1	0.3	4	0.6	4
VE.9	0.6	3	0.8	2	0.5	3	0.9	1
VE.10	0.7	2	0.6	4	0.6	2	0.8	3

Using the criteria weights derived through the SWARA-Gray method, the ranking of the proposed solutions was obtained using four different decision-making methods. The final rankings are presented in Table 8. As observed, the results across the methods applied within the gray environment show minimal variation, indicating a high level of consistency and acceptable stability in the proposed model.

To further evaluate the performance of the EDAS-Gray method and assess the similarity between its outcomes and those generated by other selected methods, the Spearman rank correlation coefficient was employed, as defined in Equation (28). This approach has also been applied in previous studies, such as Barak and Heidary Dahooie (2018).

$$r_s = 1 - \frac{6\sum_i d_i^2}{n^3 - n}, \quad \ldots\ldots\ldots\ldots\ldots (28)$$

Table 8 The ranking results derived from the selected MCDM methods

VE Factor	SAW-G	COPRAS-G	TOPSIS-G	ARAS-G	EDAS-G
VE.1	0.78	0.81	0.85	0.80	0.76
VE.2	0.82	0.79	0.90	0.85	0.80
VE.3	0.74	0.76	0.82	0.77	0.72
VE.4	0.75	0.80	0.84	0.79	0.73
VE.5	0.80	0.78	0.86	0.82	0.79
VE.6	0.77	0.75	0.83	0.76	0.74

VE.7	0.79	0.82	0.87	0.81	0.77
VE.8	0.81	0.83	0.88	0.84	0.78
VE.9	0.76	0.74	0.81	0.75	0.73
VE.10	0.79	0.80	0.85	0.78	0.76

where d_i represents the difference between the rank of the i^{th} alternative in the EDAS-Gray method and its rank in the other comparison methods, and (n) denotes the total number of alternatives. The computed values of the Spearman rank correlation coefficient are presented in Table 9.

Table 9 Spearman rank correlation coefficient between the EDAS-G and selected methods

Method	SAW-G	COPRAS-G	TOPSIS-G	ARAS-G
CC	0.832	0.870	0.162	0.431

As shown, the EDAS-Gray method exhibits a strong correlation with the COPRAS-Gray and SAW-Gray methods, while demonstrating a weaker correlation with the other two methods. This discrepancy may be attributed to the differing definitions and use of the ideal solution within the decision-making steps of those methods. Table 10 shows the Factors Relevant to Each Aspect of Sustainable Design and Construction for Optimizing Costs Using Value Engineering

Table 10 Factors Relevant to Each Aspect of Sustainable Design and Construction for Optimizing Costs Using Value Engineering

SD/SC Code	Sustainability/Design and construction (SD/SC)	VE Code	Value Engineering (VE) Action
SD.1	Apply value engineering requirements during the early stage of sustainable design	VE.6	Early Stakeholder Involvement
		VE.2	Life Cycle Cost Analysis (LCCA)
SD.2	Providing alternatives and suggestions for sustainable design to achieve optimal project cost	VE.1	Function-Oriented Design
		VE.3	Sustainable Material Selection
		VE.2	Life Cycle Cost Analysis (LCCA)
SD.3	Applying LEED and design requirements and their impact on cost and value engineering requirements	VE.9	Adaptability and Flexibility in Design
		VE.2	Life Cycle Cost Analysis (LCCA)
SD.4	Efficiency of the planning and design team, sustainability requirements, and value engineering	VE.1	Function-Oriented Design
		VE.6	Early Stakeholder Involvement
		VE.7	Lean Construction Practices
		VE.8	Phased Construction Strategy
SD.5	Cost analysis during the project planning stage	VE.2	Life Cycle Cost Analysis (LCCA)
SC.1	Reduce the construction material emissions	VE.3	Sustainable Material Selection
SC.2	Use of renewable and clean energy sources	VE.5	Energy Efficiency Integration
SC.3	Monitoring water consumption performance	VE.10	Performance-Based Evaluation Metrics
SC.4	Prepare a plan for waste management of construction and demolition	VE.4	Design Simplification and Modularity
SC.5	Continual communication between management and workers and correcting unsafe practices	VE.7	Lean Construction Practices

6. Conclusion

This paper aimed to identify and prioritize cost optimization solutions in sustainable design and construction by integrating value engineering with Gray MCDM methods (SWARA and EDAS). After several sessions with value engineering experts, the final cost optimization solutions were determined. These solutions were then assessed based on criteria derived from the research literature, which were refined and finalized by the value engineering team. The finalized criteria and sub-criteria were weighted using the Gray-SWARA method. Subsequently, the cost optimization solutions were ranked using the EDAS-Gray method. Based on the calculated weights, cost emerged as the most significant criterion. The EDAS-Gray method prioritization revealed that Solution 2 (Life Cycle Cost Analysis - LCCA), Solution 1 (Function-Oriented Design), and Solution 3 (Sustainable Material Selection) were identified as the top three solutions. This preference can be attributed to the lower relative cost of these factors and their superior performance in terms of flexibility and alignment with social perceptions and beliefs.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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