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Sustainable Practices in Highway Construction: A Green Evaluation Approach with HyperSoft Set

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Abstract: The construction industry has been significantly impacted by the global emphasis on environmental preservation, especially in the expansion of transportation infrastructure. To reduce the ecological impact of large-scale undertakings, sustainable practices are now required rather than discretionary. With an emphasis on sustainability concepts including resource efficiency, pollution prevention, and ecological preservation, this research offers a green evaluation methodology specifically designed for highway building. This study attempts to provide a systematic framework for putting greener roadways into practice by defining important criteria and assessing various building techniques. For legislators, engineers, and project managers committed to sustainable building, the findings give useful advice and insights into best practices. To ensure that advancement does not come at the price of the environment, the goal is to match the expansion of infrastructure with global environmental goals. We use the HyperSoft set to deal with different criteria and select the best values. We use MACONT method to rank alternatives.

Keywords: Sustainability; Highway Construction; Green Evaluation; HyperSoft Set; Assessment Approach.

1. Introduction

Building highways is essential to a nation's social and economic advancement because they facilitate commerce, provide connections, and foster regional development. However, the long-term environmental effects of traditional construction practices have frequently been disregarded. Incorporating sustainable techniques into highway building has become a top goal as society grows more aware of resource depletion and climate change[1], [2].

Using methods and materials that lower carbon emissions, preserve natural resources, and safeguard ecosystems is part of building a sustainable route. It necessitates a thorough strategy that considers every stage of the project lifetime, from design and planning to building and upkeep[3], [4]. It is feasible to design highways that are both environmentally conscious and useful by including sustainability concepts early in the process.

The adoption of green construction practices on highways has been driven by advances in technology, stricter environmental regulations, and growing public demand for sustainable infrastructure. Innovations such as recycled asphalt, solar-powered lighting, and wildlife corridors are becoming standard features in modern highway projects[5], [6]. These measures help to minimize the environmental footprint while also potentially reducing operational costs over the highway's lifetime.

Despite these advancements, challenges persist in the practical application of sustainable construction methods. Financial constraints, lack of technical expertise, and insufficient policy incentives can hinder widespread adoption[7], [8]s. Moreover, there is a need for robust evaluation frameworks that can accurately measure the sustainability performance of different construction practices and help stakeholders make informed decisions.

A green evaluation approach offers a systematic method to assess and compare the sustainability of various highway construction strategies. By defining clear criteria—such as energy efficiency, material sustainability, biodiversity impact, and waste management—a structured evaluation can highlight the strengths and weaknesses of each approach[9], [10]. This not only guides project selection but also identifies areas for improvement in current practices.

Integrating sustainability into highway construction also aligns with broader national and international goals, such as the United Nations Sustainable Development Goals (SDGs). Particularly, goals related to sustainable cities and communities, climate action, and responsible consumption and production are directly addressed through greener highway development practices[11], [12]. This connection strengthens the case for adopting sustainable construction methods as a strategic priority.

Furthermore, green construction practices contribute to building more resilient infrastructure capable of withstanding the impacts of climate change. Features such as permeable pavements, natural drainage systems, and erosion control measures can enhance the durability of highways under extreme weather conditions, thereby reducing future repair and maintenance costs.

In this paper, a detailed green evaluation framework is proposed to assess the sustainability of highway construction practices[13], [14]. The approach combines qualitative assessments with quantitative analysis, ensuring a balanced and comprehensive evaluation. By applying this framework to real-world case studies, the research aims to demonstrate its practicality and effectiveness in promoting greener infrastructure development.

2. Proposed Model

Smarandache introduced the concept of the HyperSoft set in 2018 and then introduced different sets[15], [16]. A Soft Set offers a straightforward approach to parameterized decision modeling that effectively handles uncertainty in an organized manner by associating attributes (or parameters) with subsets of a universal set. Numerous similar mathematical frameworks, such as fuzzy sets, neutrosophic sets, and rough sets, have been developed to handle different aspects of uncertainty. This paradigm is extended by the HyperSoft Set, which gives Soft Sets multi-attribute decision modeling. By mapping combinations of many attributes to subsets of the universal set instead of allocating a single parameter to a subset, a HyperSoft Set improves its capacity to manage complex decision-making situations[17], [18].

Let Y be a universal set and set of criteria such as $Q_1, Q_2, \dots, Q_m$. The cartesian product of these criteria can be obtained as: $Q = Q_1 \times Q_2 \times \dots \times Q_m$. The HyperSoft set over Y is a pair (A, Q) *and* $A: Q \to P(Y)$. We can define the HyperSoft Set as:

$$(A, Q) = \{(U, A(U))|U \in Q, A(U) \in P(Y)\} \tag{1}$$

$U = (U_1, U_2, \dots U_m) \in Q; U_i \in Q_i; i = 1,2, \dots, m, A(U)$ shows the subset of Y of criteria values $U_1, U_2, \dots U_m$ (2)

We show the steps of the MACONT to rank the alternatives. create the decision matrix between the criteria and alternatives such as:

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix}$$

We find three normalization matrices for the beneficial and non-beneficial criteria such as:

$$H_{ij}^1 = \frac{r_{ij}}{\sum_{i=1}^m r_{ij}} \tag{3}$$

$$H_{ij}^1 = \frac{1/r_{ij}}{\sum_{i=1}^m 1/r_{ij}} \tag{4}$$

$$H_{ij}^2 = \frac{r_{ij}}{\max r_{ij}} \tag{5}$$

$$H_{ij}^2 = \frac{\min r_{ij}}{r_{ij}} \tag{6}$$

$$H_{ij}^3 = \frac{(r_{ij} - \min r_{ij})}{(\max r_{ij} - \min r_{ij})} \tag{7}$$

$$H_{ij}^3 = \frac{(r_{ij} - \max r_{ij})}{(\min x_{ij} - \max r_{ij})} \tag{8}$$

Combine three normalization matrices into one matrix such as:

$$Q_{ij} = \alpha H_{ij}^1 + \beta H_{ij}^2 + (1 - \alpha - \beta) H_{ij}^3 \tag{9}$$

Values are $\alpha = \beta = 1/3$

Compute the distance among the reference options and every option

$$K_1(r_i) = \gamma \frac{A_i}{\sqrt{\sum_{i=1}^{m}(A_i)^2}} + (1-\gamma)\ \frac{B_i}{\sqrt{\sum_{i=1}^{m}(B_i)^2}} \tag{10}$$

$$K_2(r_i) = \delta \max\left(w_j\left(K_{ij} - K_j^-\right)\right) + (1-\delta) \min\left(w_j\left(K_{ij} - K_j^-\right)\right) \tag{11}$$

Where K_j^- refers to the average value and the value of $\delta\ and\ \gamma$ are between 0 and 1.

Compute the final score of every alternative such as:

$$K(r_i) = \frac{1}{2}\left(K_1(r_i) + \frac{K_2(r_i)}{\sqrt{\sum_{i=1}^{m}\left(K_2(r_i)\right)^2}}\right) \tag{12}$$

3. Results

This section shows the results of the proposed approach. We use ten criteria and eight alternatives to obtain the criteria weights and ranking the alternatives.

1. Material Sustainability (Values: Highly Sustainable, Moderately Sustainable, Low Sustainability)
2. Energy Consumption in Construction (Values: Low, Medium, High)
3. Pollution Control Measure (Values: Excellent, Adequate, Poor)
4. Resource Efficiency (Water, Raw Materials (Values: Very Efficient, Efficient, Inefficient)
5. Construction Waste Management (Values: Minimal Waste, Moderate Waste, Significant Waste)
6. Ecological Preservation (Values: No Impact, Minor Impact, Major Impact)
7. Use of Renewable Energy Sources (Values: Full Use, Partial Use, No Use)
8. Lifecycle Environmental Impact (Values: Very Low, Moderate, High)
9. Noise and Air Quality Management (Values: Excellent, Satisfactory, Poor)
10. Adaptation to Climate Change (Values: Highly Adaptable, Moderately Adaptable, Poorly Adaptable)

We select the best values such as:

1. C1: Highly Sustainable
2. C2: Medium
3. C3: Excellent,
4. C4: Very Efficient
5. C5: Minimal Waste
6. C6: Minor Impact
7. C7: Full Use
8. C8: Moderate,
9. C9: Excellent

10. C10: Highly Adaptable.

The options are:

1. Recycled Pavement and Aggregate Usage
2. Installation of Solar Noise Barriers
3. Rainwater Collection Systems for Highway Maintenance
4. Wildlife Corridors and Eco-Ducts Across Highways
5. Carbon Capture Techniques During Material Production
6. Deployment of Electric and Hybrid Construction Machinery
7. Smart Monitoring Systems for Pollution and Emissions Control
8. Green Roofing on Highway Service Structures (e.g., rest areas)

Three experts create the decision matrix using their opinions as shown in Figs 1-3. We integrate these matrices into a single matrix as shown in Fig 4. We compute the criteria weights such as: W1= 0.109981014, W2= 0.061165426, W3= 0.074352989, W4= 0.097550932, W5= 0.113981815, W6= 0.124222348, W7= 0.118174852, W8= 0.094196502, W9= 0.085731065, W10= 0.120643056.

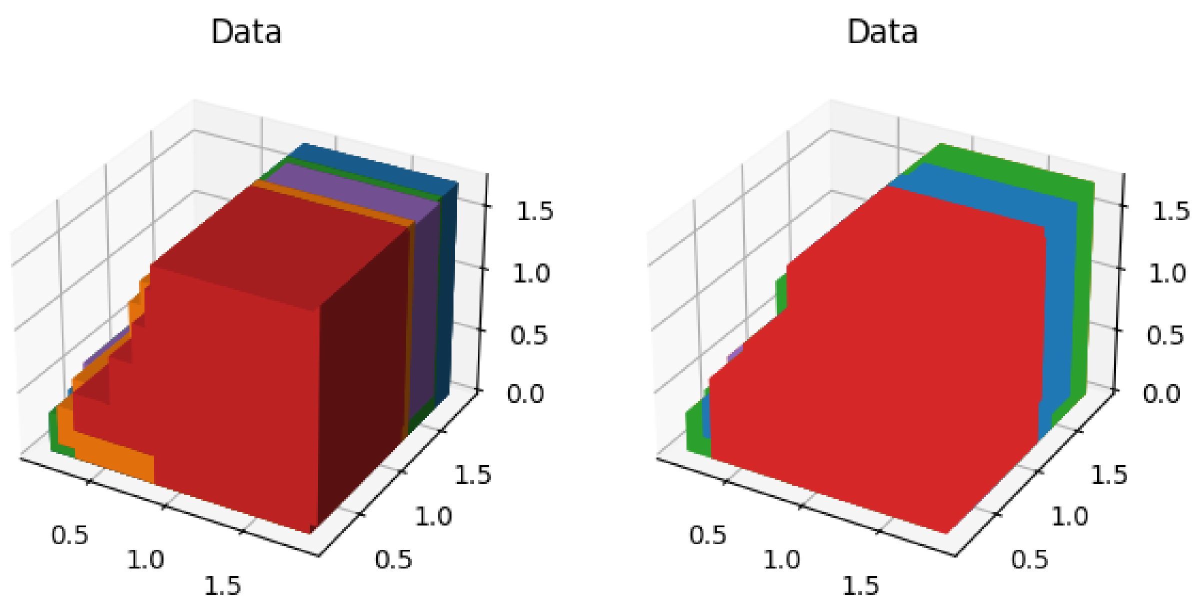

Fig 1. The first decision matrix

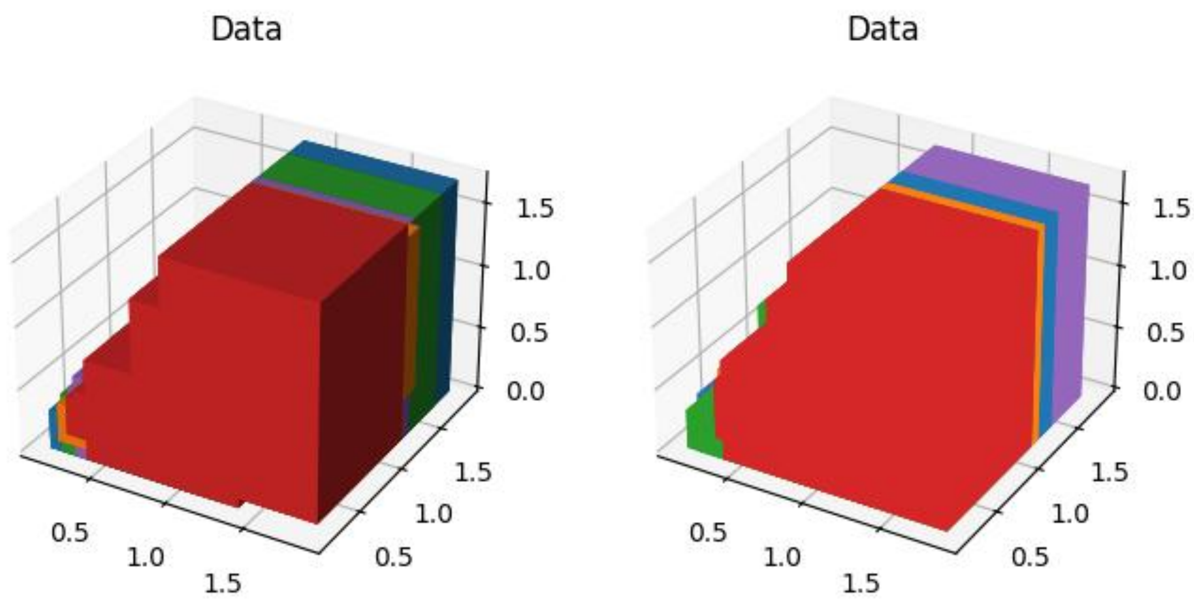

Fig 2. The second decision matrix

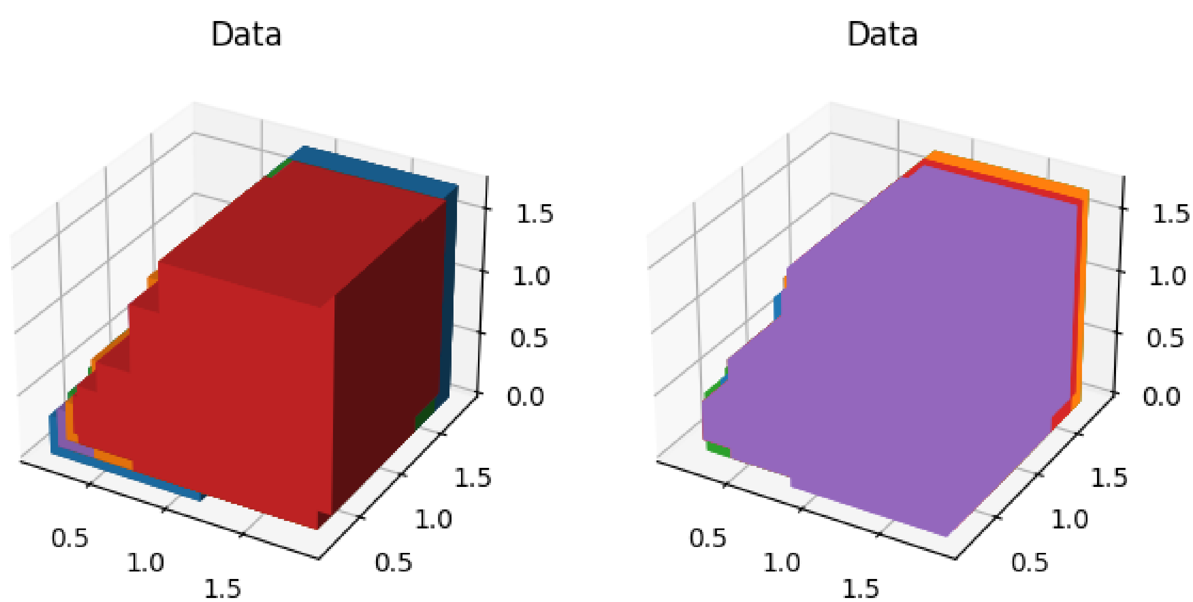

Fig 3. The third decision matrix

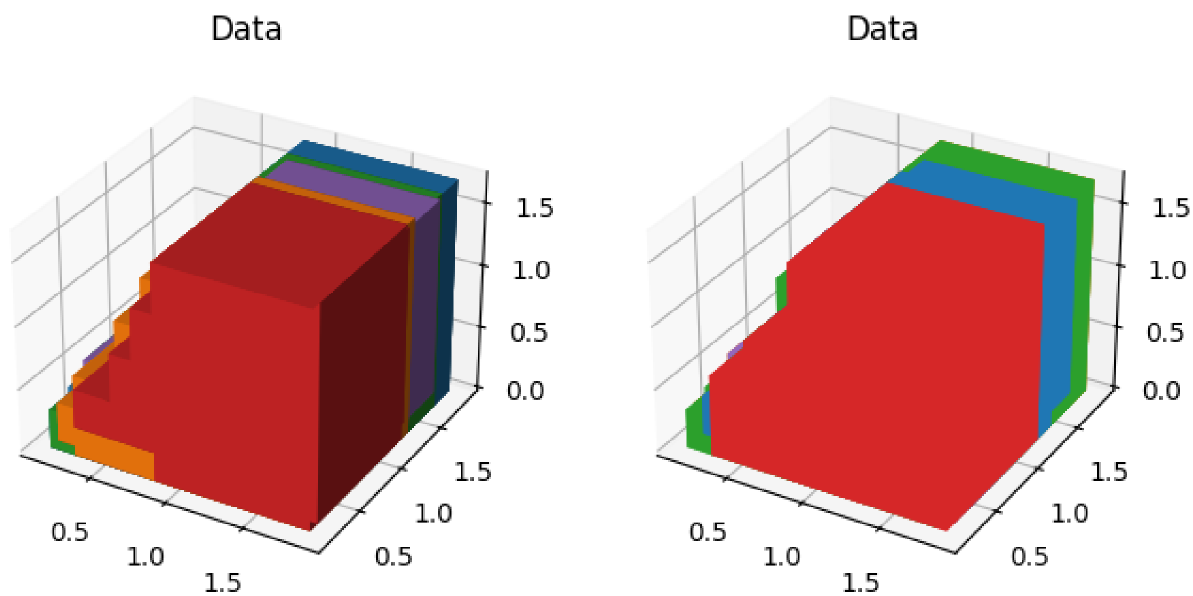

Fig 4. The combined decision matrix.

We find three normalization matrices for the beneficial and non-beneficial criteria using eqs. (3-8) as shown in Figs 5-7.

Combine three normalization matrices into one matrix using eq. (9) as shown in Fig 8.

Compute the distance among the reference options and every option using eqs. (10 and 11) as shown in Fig 9.

Compute the final score of every alternative using eq. (12) as shown in Fig 10.

Rank the alternatives as shown in Fig 11.

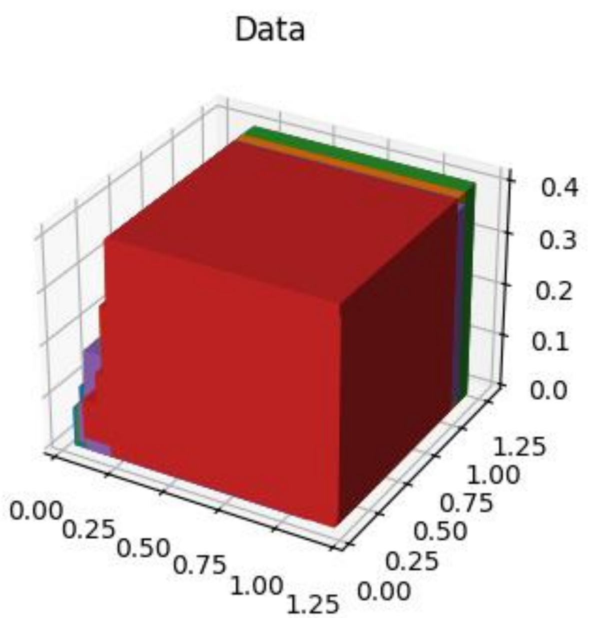

Fig 5. The first normalized values.

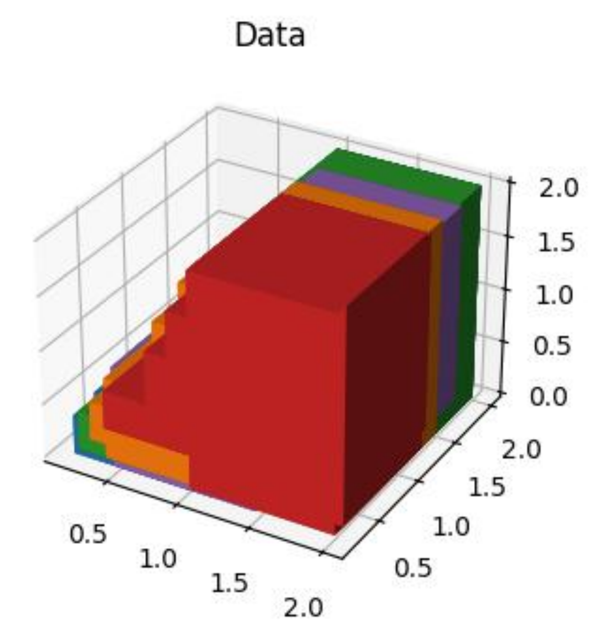

Fig 6. The second normalized values.

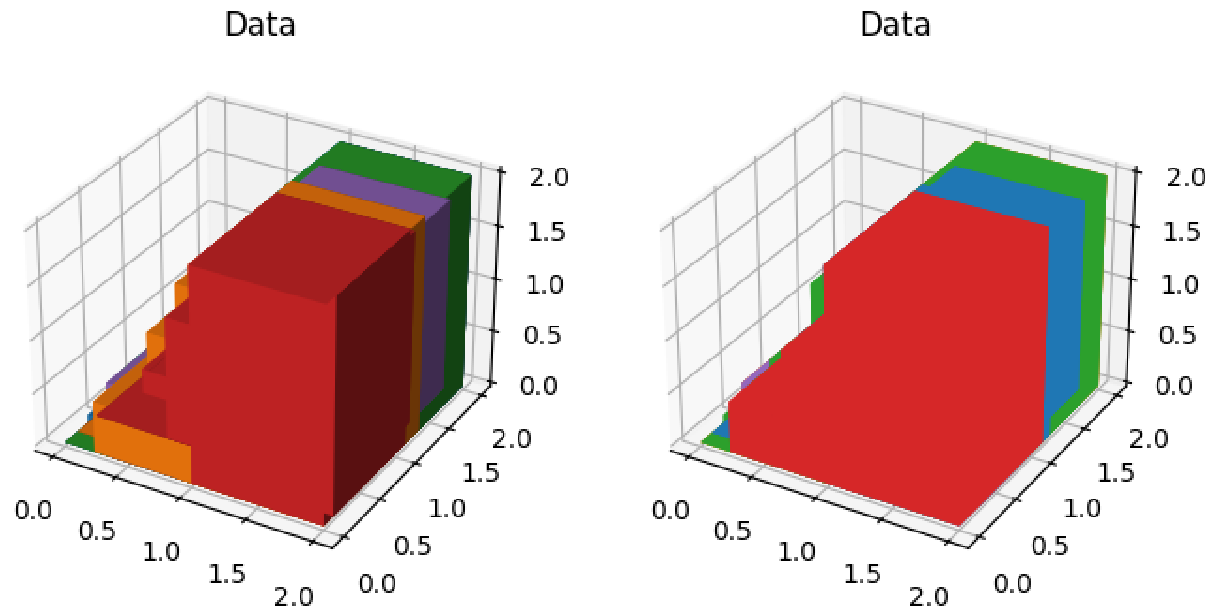

Fig 7. The third normalized values.

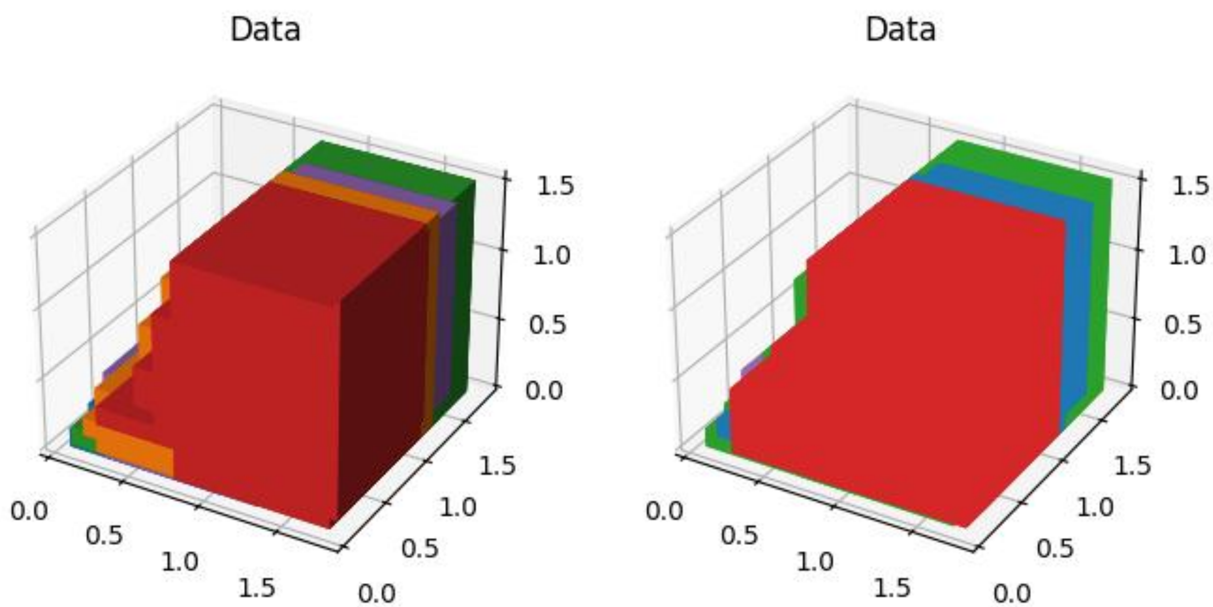

Fig 8. The integrated decision matrix.

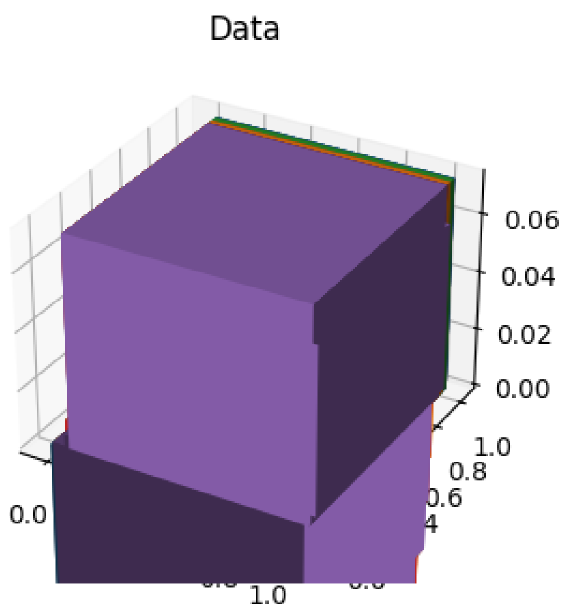

Fig 9-a. The distance among the reference options and every option.

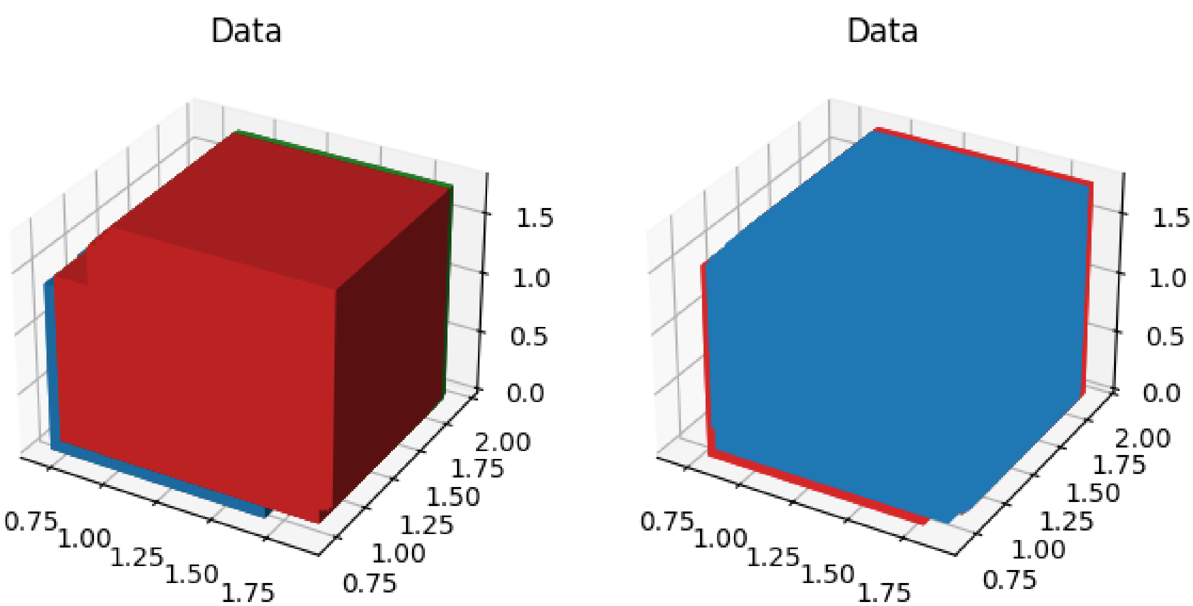

Fig 9-b. The distance among the reference options and every option.

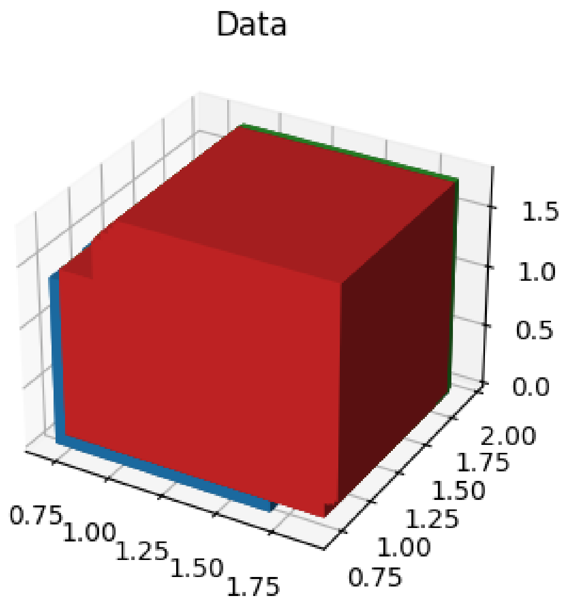

Fig 9-c. The distance among the reference options and every option.

Fig 10. The final score of every alternative.

Fig 11. The ranks of alternatives.

4. Analysis

This section shows the sensitivity analysis to show the stability of the ranks of alternatives. We split this section into two parts. In the first part, we change the value of are α and β between 0.1 and 0.9. Then we show the ranks of the alternatives under these values. Fig 12 shows the final score of new parameter values. Then we rank the alternatives under these values as shown in Fig 13.

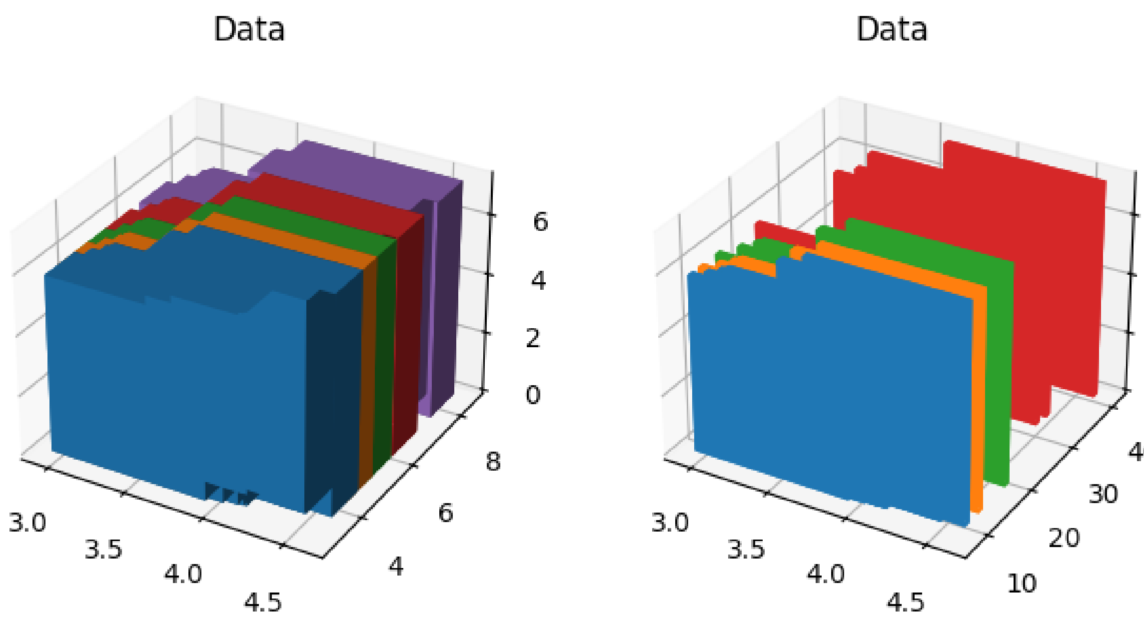

Fig 12. The final score of each alternative under new values of are α *and* β.

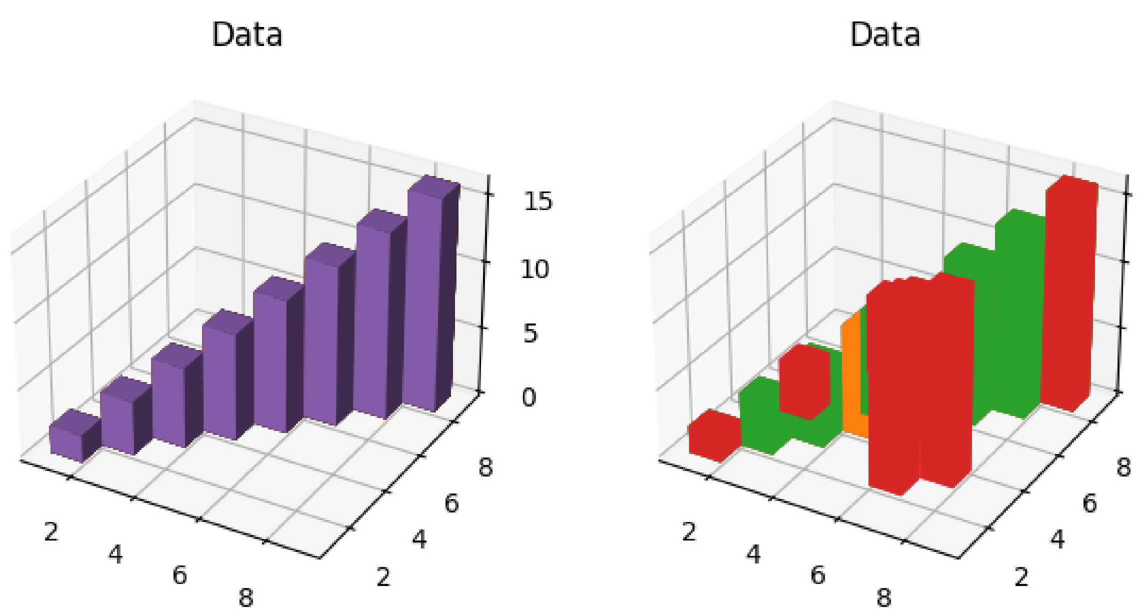

Fig 13. Ranks of the alternatives under new values of are α *and* β.

- A1:
  Consistently ranks 8th across all cases, indicating it performs the worst among all alternatives in every scenario.
- A2:
  Holds a stable 3rd position in almost all cases, showing strong and consistent

performance; however, in Case 9, its performance drops to 7th, indicating some instability under certain conditions.

- A3:
  Maintains the 5th rank across most cases, meaning it is a moderately performing alternative. Slight improvement to 4th place in Case 8, suggesting a minor fluctuation.
- A4:
  Steadily ranked 2nd in almost all cases, indicating a very high and consistent performance. Drops to 4th in Case 9, pointing to a minor decrease under certain conditions.
- A5:
  Consistently ranks 6th, indicating a below-average performance throughout. Interestingly, it improves significantly to 2nd place in Case 9, suggesting a potential for better performance under specific scenarios.
- A6:
  Consistently 7th, showing poor but stable performance across cases. Improves slightly to 3rd place in Case 9, indicating it can perform much better under favorable conditions.
- A7:
  Regularly holds 4th place in most cases, showing good and reliable performance. Slight drop to 5th place in Case 8 and 6th place in Case 9, showing some sensitivity to different situations.
- A8:
  Perfect 1st rank across all cases, demonstrating exceptional, consistent top performance with no fluctuations — the strongest and most reliable alternative.

In the second part, we change the parameter value $\delta \ and \ \gamma$ between 0.1 and 1. Then we apply the proposed approach under these values. We show the final score of each alternative as shown in Fig 14. Then we show the ranks of the alternatives as shown in Fig 15.

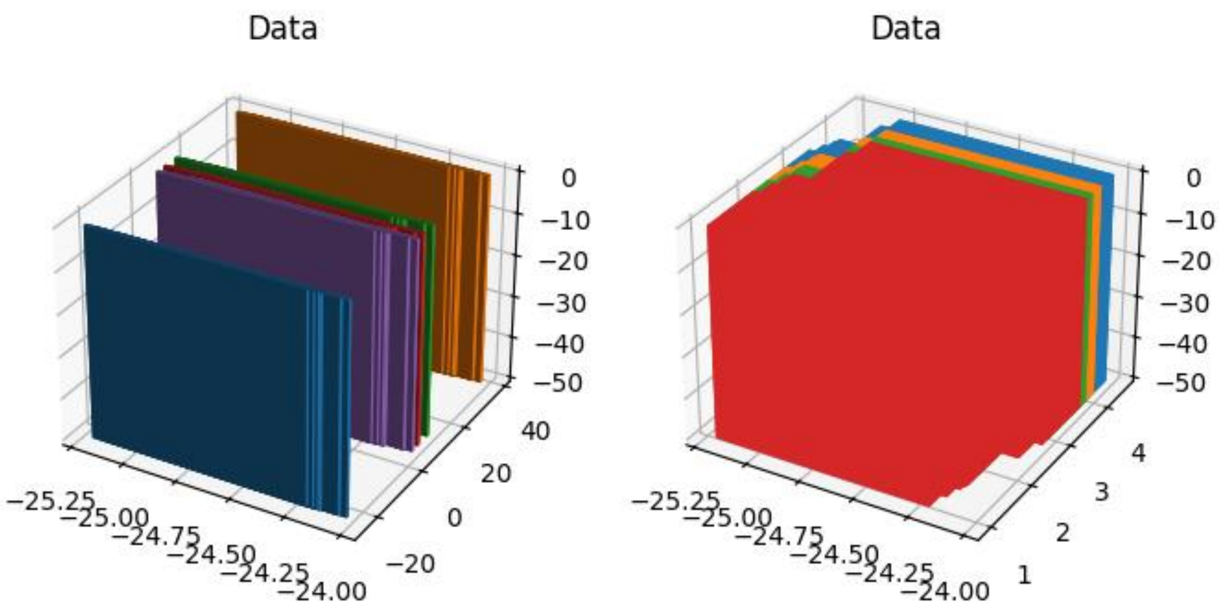

Fig 12. The final score of each alternative under new values of are δ *and* γ

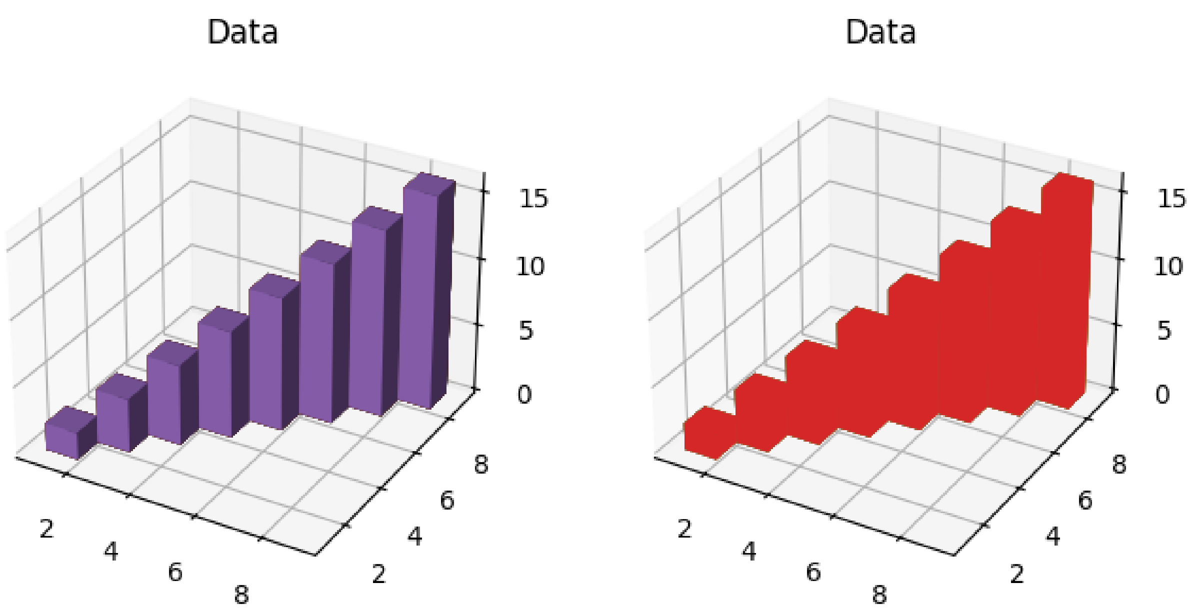

Fig 13. Ranks of the alternatives under new values of are δ *and* γ .

5. Conclusions

The urgent need for sustainable development has transformed the expectations placed on highway construction projects. Through the green evaluation approach outlined in this study, it becomes possible to systematically measure and enhance the sustainability performance of highway construction practices. Emphasizing resource efficiency, environmental protection, and long-term resilience, sustainable highway construction is not just a technical challenge but a societal necessity. We used the HyperSoft set to deal with different criteria values. The proposed approach is used to compute the criteria weights and ranking the alternatives such as MACONT method. The results are validated using the cases study with ten criteria and eight alternatives. The sensitivity analysis shows the ranks of alternatives are stable under different parameter values.

The results of this research highlight that with the right evaluation tools, policies, and collaborative efforts among stakeholders, it is possible to build highways that support both human progress and environmental stewardship. Looking ahead, continued innovation and policy support will be essential in scaling up green construction practices to meet the growing demands of a sustainable future.

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