Strong Sustainability Paradigm in TOPSIS Method: New Approach to Wind Farm Selection Problem

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Abstract. Sustainable decision-making requires balancing environmental, social, and economic objectives while minimizing trade-offs. Traditional Multi-Criteria Decision-Making (MCDM) methods, such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), often adhere to weak sustainability principles, allowing excessive linear compensation among criteria. To address this limitation, a novel STOPSIS (Sustainable TOPSIS) method is introduced – an enhanced version of TOPSIS that integrates strong sustainability paradigm by incorporating a sustainability coefficient and applying a spike suppression matrix on the input decision matrix. These modifications mitigate linear compensation, ensuring rankings that better reflect ecological and social constraints. The effectiveness of STOPSIS is demonstrated through an empirical study on offshore wind farm selection in the Baltic Sea. The results indicate significant ranking adjustments based on sustainability coefficient variations, reinforcing the method's robustness. STOPSIS offers a structured approach to sustainable decision-making, making it a valuable tool for applications in renewable energy, urban planning, and resource management.

Keywords: Sustainable Decision-Making · Multi-Criteria Decision-Making · Strong Sustainability Paradigm · TOPSIS

1 Introduction

Sustainable decision-making poses significant challenges due to the need to balance environmental, social, and economic objectives while navigating complex trade-offs [12]. Traditional Multi-Criteria Decision-Making (MCDM) methods, such as the Technique for Order Preference by Similarity to Ideal Solution [6]

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(TOPSIS), have been widely used to support sustainability-related decisions. However, these methods often align with weak sustainability principles, allowing for linear compensation where an alternative's strong performance in one criterion can offset its weak performance in another [20, 22]. This limitation can lead to rankings that do not adequately reflect the non-substitutable nature of ecological and social resources, a core principle of strong sustainability.

Despite the increasing focus on strong sustainability within MCDM research, existing methodologies remain limited in addressing the challenge of linear compensation. Prior works have proposed alternative approaches to integrate strong sustainability into decision-making processes, such as the PROSA method [27] and the SSP COPRAS [20] method. However, a significant gap remains in extending widely accepted MCDM techniques to incorporate a strong sustainability paradigm. This paper seeks to bridge this gap by introducing STOPSIS (Sustainable TOPSIS), an innovative extension of TOPSIS designed to align with strong sustainability paradigms by mitigating linear compensation effects.

The primary contribution of this study is the development of STOPSIS, which enhances traditional TOPSIS by introducing a sustainability coefficient and a spike suppression matrix. These modifications ensure that alternatives excessively advantaged by a single criterion are appropriately penalized, leading to rankings that better reflect strong sustainability principles. STOPSIS offers a more balanced and sustainable evaluation framework by reducing the compensatory effects in decision-making.

To validate the proposed method, an empirical study was conducted on the selection of offshore wind farm projects in the Baltic Sea. The study analyzed seven projects planned for development on Słupsk Bank, incorporating thirty criteria into the evaluation process. The results demonstrated that STOPSIS effectively mitigates linear compensation, significantly altering rankings as the sustainability coefficient varies. The sensitivity analysis further provided insights into rankings' stability across different compensation reduction levels.

The findings highlight the importance of integrating strong sustainability principles into MCDM frameworks. By offering a structured approach to limit compensation effects, STOPSIS can enhance decision support systems, particularly in sustainability-critical sectors such as renewable energy, urban planning, and resource management. The contributions of this research include:

- The development of STOPSIS, an extension of TOPSIS tailored to a strong sustainability paradigm.
- The introduction of the sustainability coefficient and spike suppression matrix to mitigate excessive linear compensation.
- An empirical application of STOPSIS to offshore wind farm selection, showcasing its practical utility.
- A sensitivity analysis to examine the effects of varying sustainability coefficient values on ranking outcomes, providing deeper insights into ranking stability and sustainability considerations.

The remainder of this paper is organized as follows. Section 2 presents a review of relevant literature on MCDM methods in sustainability assessment, high-

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lighting the limitations of existing approaches in addressing strong sustainability. Section 3 describes the methodological foundations of STOPSIS, including a visual demonstration of how it mitigates linear compensation effects. Section 4 describes the empirical study on offshore wind farm selection, showcasing the practical application of STOPSIS and analyzing the impact of the sustainability coefficient on ranking outcomes. The paper concludes in Section 5.

2 Literature Review

The difficulty of making sustainable decisions stems from the need to balance environmental, social, and economic goals, which frequently entails navigating complex trade-offs among these aspects [1, 12]. As organizations and societies strive to implement sustainable practices, they face numerous competing criteria that complicate decision-making, highlighting the necessity for structured and systematic approaches [18]. This complexity has led to an increasing focus on multi-criteria decision-making (MCDM) methods, which assist decision-makers in assessing, ranking, and selecting alternatives based on multiple, often conflicting, factors [25].

The efficacy of MCDM methods in sustainability-related decision-making is well established, as they enable decision-makers to address complex trade-offs that cannot be resolved by focusing on a single criterion, such as cost or environmental impact alone. These methods have been applied to various decision problems, including sustainable urban planning [11,13], waste management [5,16,17], renewable energy development [8], and resource allocation [3], allowing for the simultaneous consideration of environmental benefits, social acceptability, and economic viability.

Several studies have demonstrated the applicability of different MCDM techniques in sustainability contexts. Figueiredo et al. incorporated a fuzzy extension of AHP for selecting sustainable construction materials [4], while Kaymaz et al. employed the SWOT-AHP method to assess sustainable development goals [7]. Marzouk and Sabbah utilized a combined AHP-TOPSIS approach to evaluate social sustainability in supplier selection within the construction supply chain [9]. Similarly, Menon and Ravi applied AHP and TOPSIS for selecting sustainable suppliers in the electronics supply chain [10]. Additionally, Wątróbski et al. employed the DARIA-TOPSIS method for assessing sustainable cities and communities [24].

Strong sustainability emphasizes the critical importance of preserving natural capital and safeguarding ecological systems, in contrast to weak sustainability, which assumes the perfect substitutability of various types of capital [26]. Recently, there has been a growing interest in applying Multi-Criteria Decision Analysis (MCDA) techniques to sustainability-related decision-making. These techniques have been used to assess the sustainability of various development projects, evaluate trade-offs between different sustainability objectives, and create sustainable land use and management strategies.

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Specific MCDA methods, such as AHP [2], MAVT [14], and TOPSIS [15], due to their compensatory nature, are aligned with the assumptions of weak sustainability. However, new MCDA approaches supporting strong sustainability principles have been introduced recently.

For instance, Ziemba et al. developed the PROSA method [27] and its subsequent generalization [26], which has been applied to challenges such as selecting locations for offshore wind farms, choosing electric vehicles for public transportation, and evaluating electric scooters. Similarly, Watrobski et al. proposed the SSP COPRAS [20] and SSP-AHP [21] methods for assessing strong sustainability in healthcare. Additionally, efforts have been made to release software libraries that facilitate strong sustainability evaluation based on PROMETHEE [19] and PROSA-C [23].

The assessment of strong sustainability within MCDA research remains in its early developmental phase, with only a limited number of pioneering studies conducted to date. The relative scarcity of research in this domain underscores a significant gap, highlighting the need for further exploration and deeper investigation. This paper seeks to address this gap by contributing to the existing body of knowledge on strong sustainability assessment in the MCDA context. By introducing the novel STOPSIS method, this study seeks to make a meaningful contribution to the advancement of strong sustainability assessment within MCDA. It is expected to provide new perspectives to the practice of strong sustainability assessment within MCDA.

3 Methodology

This paper proposes a novel extension of the TOPSIS method called STOPSIS (Sustainable TOPSIS). The extension implements a strong sustainability paradigm in the TOPSIS method. This enhancement addresses the linear compensation issue in traditional TOPSIS by introducing a configurable sustainability coefficient s_j and spike suppression matrix S. The STOPSIS method reduces the compensation effect by adjusting scores based on deviations from the mean for each criterion, ensuring that alternatives highly compensated by a single criterion are penalized, leading to rankings implementing the strong sustainability paradigm.

To illustrate the objective, consider a decision problem involving three benefit criteria, C1–C3, all of which are to be maximized, and four alternatives, A1–A4. The performance values of all alternatives across the three criteria are presented in Fig. 1a. Alternative A3 significantly outperforms A1 and A2 in criterion C1, while A4 surpasses all other alternatives across all criteria. These substantial advantages in criterion values may lead to linear compensation, where the dominance of particular alternatives under specific criteria disproportionately influences the decision-making process. To mitigate this effect, the excessively high values should be adjusted—separately for each criterion—based on the mean value and sustainability coefficient s_j, while maintaining the scores of the re-

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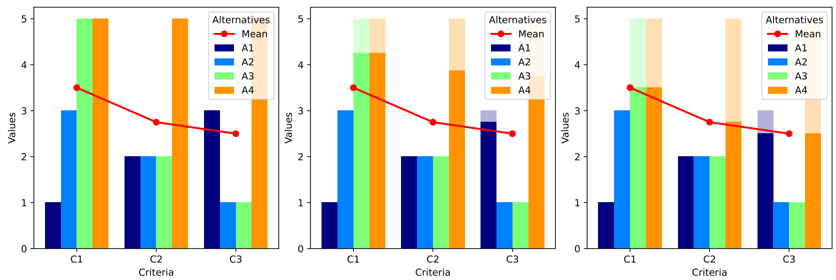

(a) (b) (c)

Fig. 1: Visual demonstration of mitigating linear compensation effect by suppressing outstanding alternative criteria performance values: a) original values; b) partial reduction with $s_j = 0.5$; c) full reduction with $s_j = 1$.

maining alternatives unchanged. Figures 1b and 1c illustrate partial and full linear compensation reduction, respectively.

To fulfill the objective above, the TOPSIS method algorithm is prepended with three additional steps at the beginning. Assuming the criterial performance decision matrix consisting of m alternatives and n criteria is already built for the TOPSIS method and is denoted as $(x_{ij})_{m\times n}$:

Step 1. Initial spike suppression matrix computation. Compute the initial value of S^*_{ij} matrix for each criterial performance value included in the decision matrix using Eq. 1:

$$S^*_{ij} = (x_{ij} - \overline{x_j})s_j \tag{1}$$

where

- x_{ij} denotes the performance value of i-th alternative under j-th criterion;
- $\overline{x_j}$ denotes the mean value from performance values under each criterion j;
- the sustainability coefficient $s_j \in <0;1>$ is a parameter that represents the level of linear compensation reduction of criteria performance. It can be assigned to selected or all criteria. If s_j is low, it denotes a low degree of linear compensation reduction for the j-th criterion. Opposite, high s_j values mean a more significant compensation reduction for the j-th criterion.

Step 2. Thresholding of the spike suppression matrix. For benefit criteria, assign 0 values to S_{ij} if the obtained values are lower than 0 to avoid decreasing values $x_{ij} < \overline{x_j}$. For cost criteria, assign 0 values to S_{ij} if the obtained values are lower than 0. Otherwise assign the original S^*_{ij} value. See Eq. 2:

$$S_{ij} = \begin{cases} S^*_{ij}, \text{ if } x_{ij} \geq \overline{x_j} \text{ (benefit criteria)} \\ 0, \quad \text{if } x_{ij} < \overline{x_j} \text{ (benefit criteria)} \\ \\ S^*_{ij}, \text{ if } S_{ij} \geq 0 \text{ (cost criteria)} \\ 0, \quad \text{if } S_{ij} < 0 \text{ (cost criteria)} \end{cases} \tag{2}$$

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This step is important as it prevents alternatives with relatively lower performance from being assigned even worse performance values.

Step 3. Application of the spike suppression on the original decision matrix. Subtract S_{ij} values from performance values x_{ij} contained in the original decision matrix S as shown in Eq. (3):

$$x_{ij}^{\downarrow} = x_{ij} - S_{ij} \tag{3}$$

These novel initial three steps are then followed by the complete set of classic TOPSIS steps, as described in [6], i.e. normalization of the adjusted decision matrix $x_{ij}^{\downarrow}$; computation of weighted normalized decision values; identification of positive and negative ideal solutions; calculation of distances to ideal solutions. The procedure is finalized by computing TOPSIS scores and ranking alternatives.

4 Empirical Study

The empirical study examined seven proposed offshore wind farm projects in the Baltic Sea: Bałtyk II (A1) and Bałtyk III (A2) by Polenergia/Equinor, Baltica 2 (A3) and Baltica 3 (A4) by PGE/Orsted, FEW Baltic II (A5) by RWE Offshore, Baltic Power (A6) by PKN Orlen/Northland Power, and B-C Wind (A7) by Ocean Winds. These projects were all planned for development on Słupsk Bank, located off the Polish coast at approximately 54°58'N, 16°36'E.

4.1 Dataset and Baseline Ranking

The study assessed the projects based on 30 different criteria: power (C1), gross area (C2), distance from the shore (C3), length of the underwater expert cable (C4), average depth (C5), maximum depth (C6), remaining time to the planned start-up date (C7), basing utilization efficiency (C8), predicted annual production (C9), coverage of household energy demand (C10), new direct jobs (C11), new indirect jobs (C12), CO2 reduction (C13), SO2 reduction (C14), dust reduction (C15), education support (C16), local communities support (C17), coal savings in tons (C18) and PLN (C19), savings on CO2 emission permits (C20), concession fee (C21), location permit (C22), local content during construction phase (C23) and exploatation phase (C24), installation port investment (C25), entrepreneurship support (C26), innovation support (C27), investment costs - CAPEX (C28), annual operating costs - OPEX (C29), liquidation costs - DECEX (C30).

Criteria C1, C2 and C8-C27 are benefit criteria and should be maximized, whereas criteria C2-C7 and C28-C30 are cost criteria and should be minimized. In this study, the weights of all criteria were set to an equal value of $\frac{1}{30} \approx 0.033$.

To keep the paper concise, the dataset is not included here; however, the latest version can be accessed in a dedicated GitHub repository[4].

[4] https://github.com/mcdait/datasets/blob/main/windfarms202502/offshore-dataset.csv

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Table 1: Evaluation results of the 7 offshore wind farms projects: A) baseline ranking; B) partial linear compensation reduction using $s_j = 0.5$; C) full linear compensation reduction using $s_j = 1$

Case	Ranks							Scores						
	A1	A2	A3	A4	A5	A6	A7	A1	A2	A3	A4	A5	A6	A7
A	5	4	1	3	6	2	7	0.455	0.494	0.611	0.525	0.389	0.599	0.308
B	5	4	2	3	6	1	7	0.522	0.557	0.621	0.588	0.394	0.658	0.322
C	4	2	5	3	6	1	7	0.658	0.690	0.635	0.685	0.405	0.749	0.353

A criterial performance matrix was constructed using the dataset and processed through a TOPSIS method implementation, incorporating criteria types (cost/benefit) and equal weights to generate a baseline ranking. The results of this baseline evaluation are presented in Table 1, row A. Among the alternatives, A1 ranks highest with a score of 0.455, followed by A6 with 0.599 and A4 with 0.525.

4.2 Linear Compensation Reduction

Once the baseline ranking was obtained, subsequent experiments were performed to study the effect of the proposed linear compensation reduction approach. At first, the sustainability coefficient s_j was set to 0.5, and spike suppression on the decision matrix was performed. Subsequently, s_j was set to 1.0, and another spike-suppressed decision matrix was produced.

The effect of the spike suppression is presented on subplots in Fig. 2. For each criterion and alternative, three bars are plotted. The left one represents the original criterial performance, whereas the middle and right ones represent values with partial ($s_j = 0.5$) and full compensation reduction ($s_j = 1.0$), achieved through suppression of the spiking values.

Consider criterion C1, where alternatives A3, A4, and A6 demonstrate significantly higher values compared to the other alternatives. In particular, A3, with a value of 1498, exceeds the values of A5 and A7 (350 and 400, respectively) by more than a factor of four and is twice as high as A1 and A2, both of which have values of 720. This substantial advantage in criterion C1 may lead to linear compensation, wherein A3's strong performance overshadows its weaker performance in other criteria, specifically C3, C16, C17, C25, C26, C28, C29, and C30.

When our proposed novel approach is applied to the decision matrix, the performance values of A3, A4, and A6 are adjusted downward, while the values of A1, A2, A5, and A7 remain unchanged. The extent of this reduction is influenced by two factors: the degree to which an alternative exceeds the mean value for the given criterion and the magnitude of the s_j sustainability coefficient.

Among the 30 subplots in Fig. 2, the subplot for criterion C4 is particularly noteworthy. As a cost criterion, lower values are preferable. Notably, in the original decision matrix, alternatives A3–A5 have negative values for this criterion,

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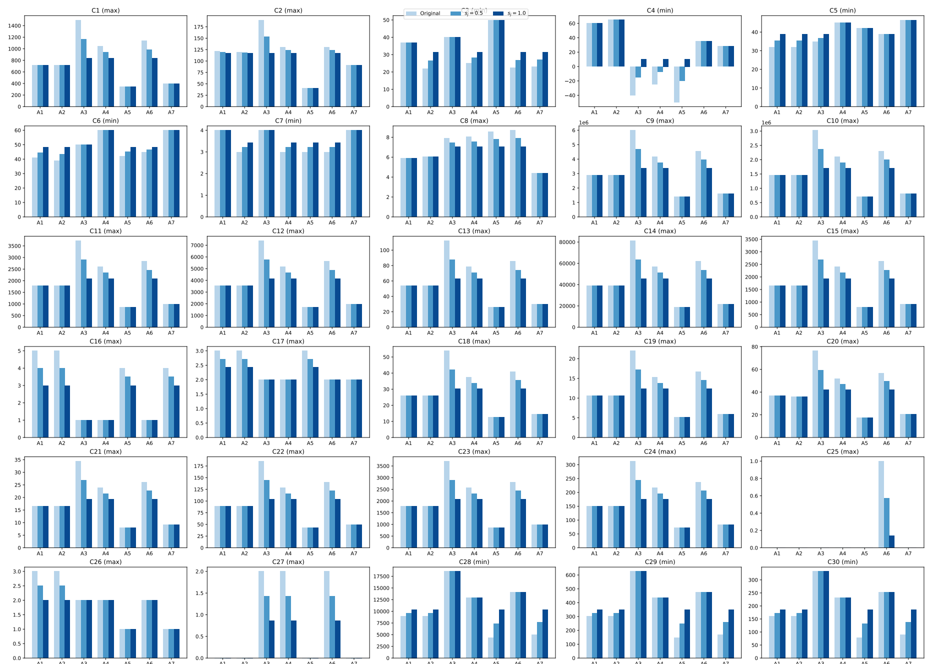

Fig. 2: Visualization of reduction of criteria compensation. For each criterion and alternative left bar presents original criterial performance, middle bar presents value with partial compensation reduction ($s_j = 0.5$) and right bar presents value with full compensation reduction ($s_j = 1.0$)

indicating superior performance. In contrast, the majority of the remaining alternatives exhibit positive values for C4. When applying $s_j = 0.5$, the values for A3, A4, and A5 become less negative, moving closer to zero. With $s_j = 1$, these values turn positive, though they remain lower than those of A1, A2, A6, and A7. However, the difference is significantly reduced, thereby mitigating the risk of linear compensation.

Subsequently, the two modified decision matrices were applied to the TOPSIS method, resulting in two additional sets of rankings. These rankings are presented in Table 1, in rows B and C, respectively. When linear compensation is partially reduced, alternatives A3 and A6 swap their rankings, while alternative A4 retains its 3rd position. With a further reduction in linear compensation, using $s_j = 1$, alternative A4 experiences a significant drop to 5th place. The top-ranked alternative is once again A6, followed by A2, which moves up from its original 4th position, and A3, which remains in 3rd place.

While the scores show a strong correlation across all three rankings (see Fig. 3a), a notable decrease in correlation is observed between the baseline ranking and the ranking with full linear compensation reduction (0.61, see Fig. 3b). This

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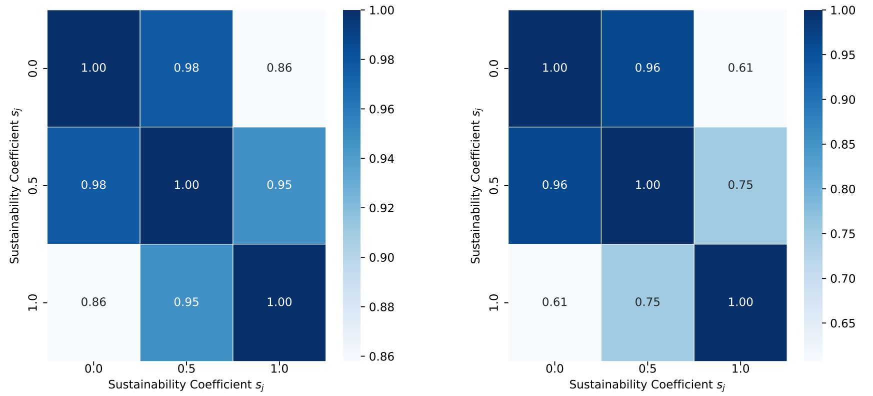

(a) scores (b) ranks

Fig. 3: Correlation between A) scores and B) ranks obtained with TOPSIS with unprocessed data ($s_j = 0.0$), partial compensation reduction ($s_j = 0.5$) and full compensation reduction ($s_j = 1.0$)

demonstrates that the proposed approach effectively reduced linear compensation in the TOPSIS method, leading to significant changes in the results.

4.3 Sensitivity Analysis

The final experiment in this study aimed to conduct a comprehensive sensitivity analysis to examine how variations in the sustainability coefficient, s_j, (representing a reduction in linear compensation) affect the rankings generated by the TOPSIS method. Eleven rankings were generated by setting s_j to values ranging

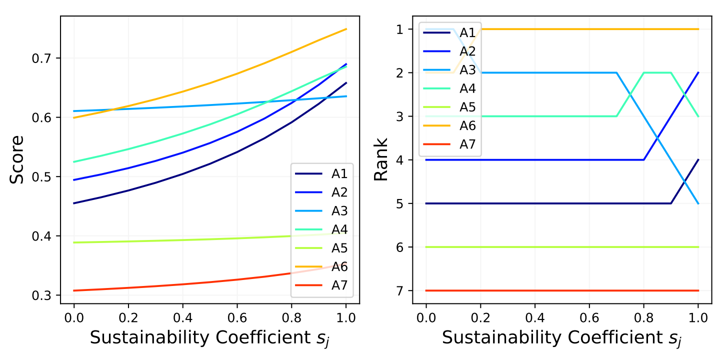

Fig. 4: Sensitivity analysis of the solution depending on the s_j coefficient value.

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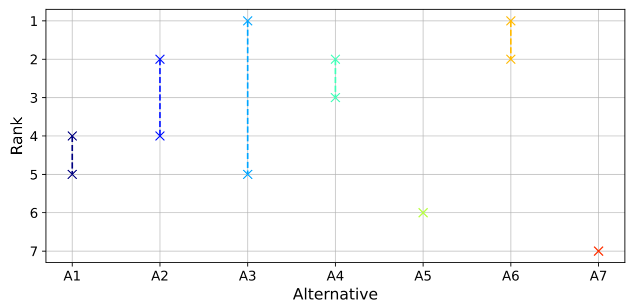

Fig. 5: Ranges of ranks obtained by each alternative during the s_j coefficient sensitivity analysis.

from 0 to 1.0 in increments of 0.1. The resulting scores and ranks from all 11 rankings were plotted and are presented in Fig. 4.

Upon analyzing the score plot, a clear trend emerges for each alternative (A1–A7). Each alternative demonstrates an increasing score as the sustainability coefficient s_j is raised. The most significant increase in score is observed for alternatives A1 and A2, both of which exhibit a strongly rising and nearly identical curve. Alternatives A4 and A6 also display a notable increase, albeit with a less pronounced slope compared to A1 and A2. Alternative A3 shows a moderate upward trend. In contrast, alternatives A5 and A7 experience the smallest increase in score as linear compensation decreases, with A5 showing an almost flat trend on the graph, suggesting minimal growth.

The analysis of the rankings plot reveals several notable shifts. Alternative A1 maintains its position in 5th place within the range of $s_j = 0.0 - 0.9$, before advancing to 4th place at $s_j = 1.0$. Alternative A2 initially holds 4th place but gradually moves up within the range of $s_j = 0.8 - 1.0$, ultimately securing 2nd place. Alternative A3, conversely, drops from 1st to 5th place. Alternative A4 presents a distinct pattern: it starts in 3rd place but rises to 2nd place in the range of $s_j = 0.8 - 0.9$, only to return to its initial 3rd place in the full compensation reduction ranking. Alternatives A5 and A7 maintain their respective positions, with A5 in 6th place and A7 in 7th place. Finally, A6, which begins in 2nd place, shows an upward trend between $s_j = 0.1 - 0.2$ and advances to the 1st place. Fig. 5 shows the visualization of the complete ranges of ranks each alternative obtained during the s_j sensitivity analysis.

Finally, the distances of each alternative to the positive and negative ideal solutions, and how these distances change as linear compensation is reduced, are presented in the plot in Fig. 6. Each observation is represented as a dot. Observations with lower values of s_j appear almost transparent, while the markers become progressively more opaque as s_j increases. For each alternative, the three specific observations from Table 1 (i.e., $s_j \in \{0, 0.5, 1\}$) are additionally marked with a + symbol.

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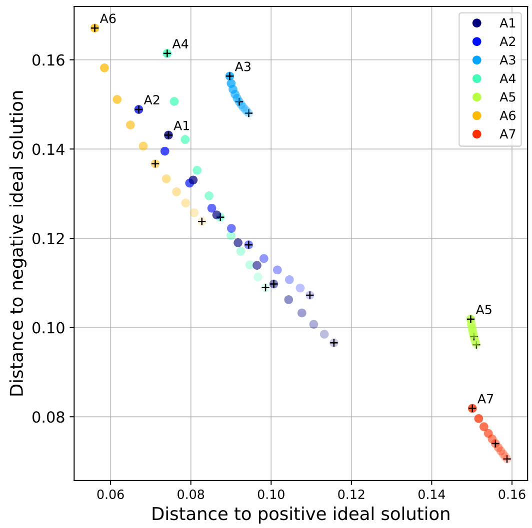

Fig. 6: Visualization how criteria compensation reduction impacts distances of alternatives to positive and negative ideal solutions.

It is evident that, for each alternative, as the linear compensation decreases, the distance to the positive ideal solution decreases, while the distance to the negative ideal solution increases. This trend holds for all alternatives A1–A7, although the change in distance for A3, A5, and A7 is minimal. In contrast, the change for A1, A2, A4, and A6 is more pronounced.

A detailed analysis of Fig. 6, together with the scores in Fig. 4, helps to clarify how the scores for all alternatives increase, with none of them showing a decrease in score (although rank swapping occurs). Additionally, this analysis explains why A3 drops from rank 2 to rank 5 when the value of s_j becomes sufficiently high.

5 Conclusions

This study introduced STOPSIS, a novel extension of the TOPSIS method, designed to align with the strong sustainability paradigm by mitigating the effects of linear compensation in multi-criteria decision-making. Conventional TOPSIS is prone to linear compensation, which can disproportionately favor alternatives that excel in a limited number of criteria while underperforming in others. By integrating the sustainability coefficient s_j and the spike suppression matrix S, STOPSIS ensures that alternatives with extreme performance in certain criteria do not overly dominate the ranking process, leading to a more balanced and sustainable decision-making framework.

The empirical study on offshore wind farm project selection demonstrated the effectiveness of STOPSIS in practice. Significant changes in rankings were

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observed with varying levels of linear compensation reduction, highlighting the necessity of incorporating strong sustainability principles into decision-making processes. The sensitivity analysis allowed to further explore how varying s_j values influence ranking outcomes.

The findings indicate that STOPSIS effectively reduces linear compensation and provides a more equitable assessment of alternatives, which is crucial in sustainability-driven decision contexts. The results suggest that integrating strong sustainability considerations into MCDM methodologies can enhance decision support systems, particularly in domains where ecological integrity and the balance between environmental, social, and economic factors must be prioritized.

The main highlights of this study include:

- The introduction of STOPSIS, an enhanced version of TOPSIS tailored for strong sustainability.
- The integration of the sustainability coefficient s_j and spike suppression matrix S to mitigate excessive linear compensation.
- An empirical application to offshore wind farm selection, demonstrating the method's practical effectiveness.
- A sensitivity analysis exploring how the sustainability coefficient s_{ij} affects rankings across its full range from 0 to 1, providing deeper insights into ranking stability and sensitivity.

Future research should explore the application of STOPSIS across diverse sustainability challenges, such as urban planning, resource allocation, and circular economy strategies. Additionally, refining the method by incorporating dynamic weighting schemes and adaptive sustainability coefficients could further enhance its applicability and responsiveness to varying decision-making scenarios.

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