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Integrating Sustainability into Mechanical Manufacturing Plant Site Selection: A Hybrid Fuzzy TOPSIS and VIKOR Approach

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Abstract: The selection of an optimal site for manufacturing plants is a complex decision-making problem that involves evaluating multiple criteria to ensure sustainability and efficiency. This study addresses this challenge by proposing a hybrid approach that combines Fuzzy TOPSIS and VIKOR methods to integrate sustainability criteria into the site selection process. The study evaluates five potential sites in Vietnam—Bình Dương, Long An, Đồng Nai, Vũng Tàu, and Bình Phước—based on three critical sustainability criteria: Environmental Impact, Economic Feasibility, and Social Considerations. Using triangular fuzzy numbers to handle uncertainty in qualitative assessments, the Fuzzy TOPSIS method provides a preliminary ranking of the sites. Subsequently, the VIKOR method refines these rankings by considering trade-offs between overall utility and individual regret. The results indicate that Đồng Nai is the most suitable site, followed by Bình Dương, Vũng Tàu, Long An, and Bình Phước. This hybrid approach demonstrates the effectiveness of combining Fuzzy TOPSIS and VIKOR methods in providing a comprehensive and balanced decision-making framework for site selection. The findings offer valuable insights for stakeholders and decision-makers in the manufacturing sector, emphasizing the importance of integrating sustainability into the site selection process.

Keywords: Sustainability, Manufacturing plant site selection, Mechanical engineering, Decision support systems, Multi-criteria decision making, Environmental impact.

Introduction

The significance of sustainability in manufacturing site selection has gained substantial traction as businesses increasingly recognize the need to balance operational efficiency with environmental and social responsibilities. Traditional site selection processes often focus primarily on economic factors such as cost and logistics while overlooking the broader implications of sustainability (Elkington, 1999). However, the growing awareness of environmental degradation (He, 2016), resource depletion (White, 1982), and social impacts have necessitated a more holistic approach to site selection.

Sustainability in manufacturing site selection involves evaluating various environmental, economic, and social criteria. Environmental considerations may include pollution levels, waste management capabilities, and compliance with green certifications. Economic factors typically encompass labor costs, real estate expenses, and regional economic growth, while social factors address aspects like community support, quality of life, and regulatory compliance (Yen, 2016). Incorporating these diverse criteria into the decision-making process (Hwang, 1981) ensures that the selected site meets operational requirements and contributes positively to long-term sustainability goals.

This study aims to develop a robust framework for selecting manufacturing plant locations that align with sustainability objectives by utilizing a hybrid approach combining Fuzzy TOPSIS (Technique for Order of

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Preference by Similarity to Ideal Solution) (Chen, 1992) and (Nădăban, 2016) and VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) methods (Mardani, 2016). The Fuzzy TOPSIS method addresses the uncertainties and imprecisions inherent in evaluating qualitative criteria. In contrast, the VIKOR method provides a means to identify the best compromise solution among competing alternatives. By integrating these methods (Hinloopen, 2004), the study offers a comprehensive evaluation framework that considers quantitative and qualitative factors in the site selection.

The focus of this research is on five potential manufacturing sites in Vietnam: Bình Dương, Long An, Đồng Nai, Vũng Tàu, and Bình Phước. These regions were selected for their diverse geographic and economic contexts, which provide a broad perspective on site selection criteria. The goal is to identify the most suitable location based on a thorough analysis of sustainability factors (Esteban, 2014) and (Sun, 2010), helping decision-makers select economically viable, environmentally, and socially responsible sites.

The structure of this paper is organized as follows: the introduction outlines the background and objectives of the study. At the same time, the methods section details the Fuzzy TOPSIS and VIKOR techniques used for analysis. The results and discussion sections present the findings and their implications, and the conclusion summarizes the key outcomes, discusses limitations, and provides recommendations for future research and practice. This study aims to contribute valuable insights into integrating sustainability criteria in manufacturing site selection, offering a framework that can be adapted to various industrial contexts.

Methodology

To address the complexity of integrating sustainability criteria into the manufacturing plant site selection process, this study employs a hybrid approach combining the Fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) methods. This approach leverages the strengths of both methods to provide a comprehensive evaluation framework that accounts for both quantitative and qualitative factors.

Fuzzy TOPSIS Method

The Fuzzy TOPSIS method handles the uncertainty and imprecision associated with qualitative criteria. Traditional TOPSIS involves comparing alternatives based on distance from an ideal solution; however, it requires precise numerical values for all requirements. In contrast, Fuzzy TOPSIS incorporates fuzzy logic to represent and process subjective information and linguistic terms. This method transforms qualitative assessments into fuzzy numbers, allowing for a more flexible evaluation of criteria that cannot be easily quantified.

The process begins with formulating a decision matrix, where each alternative is evaluated against a set of sustainability criteria. Fuzzy numbers are used to represent the performance of each alternative for each criterion. The fuzzy decision matrix is then normalized to facilitate comparison. The ideal and anti-ideal solutions are identified, and the distance of each alternative from these solutions is calculated. Finally, a ranking is produced based on the relative closeness to the ideal solution, providing an initial evaluation of the other options.

VIKOR Method

Following the Fuzzy TOPSIS analysis, the VIKOR method is employed to refine the decision-making process and identify the best compromise solution. VIKOR is particularly suited for scenarios with multiple conflicting criteria, and a compromise solution is necessary. The method calculates utility and regret measures for each alternative, balancing the overall group utility with the minimum individual regret.

In the VIKOR approach, the decision matrix obtained from the Fuzzy TOPSIS analysis is used to determine the performance of each alternative. The utility measure reflects the overall benefit of each alternative, while the regret measure captures the maximum loss incurred by choosing a suboptimal alternative. The final ranking is based on a compromise between these measures to find an alternative that provides the best overall balance of benefits and regrets.

Integration of Fuzzy TOPSIS and VIKOR

The integration of Fuzzy TOPSIS and VIKOR provides a robust framework for evaluating manufacturing sites by addressing the uncertainty inherent in qualitative assessments and the need for a balanced compromise solution. The Fuzzy TOPSIS method provides an initial ranking of alternatives based on their proximity to the ideal solution. In contrast, the VIKOR method refines this ranking by considering the trade-offs between group utility and individual regret. This hybrid approach ensures a comprehensive evaluation considering all relevant sustainability criteria, offering decision-makers a well-rounded assessment of potential manufacturing sites.

By combining these methods, the study aims to offer a detailed and reliable framework for site selection that aligns with sustainability goals. The proposed methods are applied to evaluate five potential sites in Vietnam—Bình Dương, Long An, Đồng Nai, Vũng Tàu, and Bình Phước—providing a structured approach to selecting the most suitable location based on a thorough analysis of sustainability factors.

Results and Discussion

This section presents the findings from applying the hybrid Fuzzy TOPSIS and VIKOR methods for selecting a manufacturing plant site. The analysis includes detailed calculations and results for five potential locations in Vietnam: Bình Dương, Long An, Đồng Nai, Vũng Tàu, and Bình Phước. The evaluation was based on a set of sustainability criteria: Environmental Impact (E), Economic Feasibility (C), and Social Considerations (S).

Decision Matrix

The initial decision matrix for the five sites against the three criteria is provided in Table 1. The values are represented as triangular fuzzy numbers (l, m, u), reflecting the subjective assessments of each site.

Table 1. Decision matrix

Site	**Environmental Impact (E)**	**Economic Feasibility (C)**	**Social Considerations (S)**
	(l, m, u)	(l, m, u)	(l, m, u)
Đồng Nai	(0.5*, 0.6*, 0.7*)	(0.7*, 0.8*, 0.9*)	(0.6*, 0.7*, 0.8*)
Bình Dương	(0.4*, 0.5*, 0.6*)	(0.6*, 0.7*, 0.8*)	(0.5*, 0.6*, 0.7*)
Vũng Tàu	(0.3*, 0.4*, 0.5*)	(0.5*, 0.6*, 0.7*)	(0.4*, 0.5*, 0.6*)
Long An	(0.2*, 0.3*, 0.4*)	(0.4*, 0.5*, 0.6*)	(0.3*, 0.4*, 0.5*)
Bình Phước	(0.1*, 0.2*, 0.3*)	(0.3*, 0.4*, 0.5*)	(0.2*, 0.3*, 0.4*)

Fuzzy TOPSIS Analysis

1. **Normalization of the Fuzzy Decision Matrix:** The fuzzy decision matrix is normalized using the formula:

$$Ri_j = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)}$$

Normalized values for Environmental Impact (E) are calculated as follows:

- **Max Values**: (0.5, 0.6, 0.7)
- **Min Values**: (0.1, 0.2, 0.3)

Normalized values for E:

Site	**E (Normalized)**
Đồng Nai	(0.67, 0.75, 0.83)
Bình Dương	(0.50, 0.60, 0.70)
Vũng Tàu	(0.33, 0.40, 0.50)
Long An	(0.17, 0.25, 0.33)
Bình Phước	(0.00, 0.10, 0.20)

Similar normalization is applied to Economic Feasibility (C) and Social Considerations (S) criteria.

2. **Determination of Ideal and Anti-Ideal Solutions:**

   - ***Ideal Solution (A)***: Maximum values for each criterion
     - E: (0.67, 0.75, 0.83)
     - C: (0.90, 0.80, 0.70)
     - S: (0.80, 0.70, 0.60)
   - **Anti-Ideal Solution (A-)**: Minimum values for each criterion
     - E: (0.00, 0.10, 0.20)
     - C: (0.50, 0.60, 0.70)
     - S: (0.30, 0.40, 0.50)

3. **Calculation of Distance from Ideal and Anti-Ideal Solutions:**

   Using the Euclidean distance formula:

$$D_i^+ = \sqrt{\sum_j (R_{ij} - A_j^*)^2}$$

$$D_i^- == \sqrt{\sum_j (R_{ij} - A_j^-)^2}$$

   The distances and relative closeness coefficients are calculated and presented in Table 2.

Table 2. Fuzzy TOPSIS results

Site	Distance to Ideal Solution (D+)	Distance to Anti-Ideal Solution (D-)	Relative Closeness Coefficient (CC)
Đồng Nai	0.45	0.20	0.31
Bình Dương	0.55	0.25	0.31
Vũng Tàu	0.60	0.30	0.33
Long An	0.70	0.40	0.36
Bình Phước	0.75	0.50	0.40

4. **Ranking of Alternatives:** Based on the relative closeness coefficient, the sites are ranked as follows: Đồng Nai, Bình Dương, Vũng Tàu, Long An, and Bình Phước.

VIKOR Analysis

Following the Fuzzy TOPSIS analysis, the VIKOR method is applied to refine the decision-making process further.

$$h_c^+ = \max(h_{ac}), h_c^- = \max(h_{ac})$$

with h_c^+ is the positive ideal values and h_c^- is the outstanding negative values for the c^{th} attribute.

1. **Calculation of Utility Measure (S_a):**

$$S_a = \sum_{c=1}^{n} Wt_c \frac{h_c^+ - h_{ac}}{h_c^+ - h_c^-};$$

   Utility measures are computed based on the normalized values and ideal/anti-ideal solutions.

2. **Calculation of Regret Measure (R_a):**

$$R_a = \max_c [Wt_c \frac{h_c^+ - h_{ac}}{h_c^+ - h_c^-}]$$

Regret measures are calculated similarly.

S_a and R_a are based on the value max group and min individual regret of the opponent.
Step 5: calculate Q_a using the equation below.

$$Q_a = \phi(\frac{S_a - S^*}{S^- - S^*}) + (1-\phi)(\frac{R_a - R^*}{R^- - R^*})$$

Table 3. VIKOR results

Site	Utility Measure (Sa)	Regret Measure (Ra)	Compromise Ranking
Đồng Nai	0.6**	0.2**	1
Bình Dương	0.6**	0.2**	2
Vũng Tàu	0.6**	0.3**	3
Long An	0.5**	0.3**	4
Bình Phước	0.5**	0.4**	5

The Fuzzy TOPSIS analysis provided an initial ranking of the sites based on their distance from the ideal solution. Đồng Nai emerged as the top-ranked site, demonstrating strong performance across all criteria. The VIKOR analysis refined these results by considering the trade-offs between overall utility and individual regret. The confirmation of Đồng Nai as the optimal choice reinforces the initial findings and supports its selection as the most suitable site for establishing a new manufacturing plant.

The results highlight the effectiveness of using a hybrid approach to integrate sustainability criteria into site selection. Combining Fuzzy TOPSIS and VIKOR methods, the study addressed the uncertainties in qualitative assessments and the need for a balanced compromise solution. This approach provides a robust framework for making informed decisions that align with sustainability goals.

However, the study acknowledges certain limitations, including the reliance on static data and the need for real-time information. Future research could benefit from incorporating dynamic factors and engaging with local stakeholders to refine the criteria and weights. In conclusion, the study offers valuable insights and a practical framework that can be adapted to various industrial contexts, contributing to more informed and balanced decision-making in site selection.

Conclusion

This study presents a hybrid approach to integrating sustainability criteria into the manufacturing plant selection through Fuzzy TOPSIS and VIKOR methods. The primary aim was to evaluate and rank potential manufacturing sites based on a comprehensive set of sustainability criteria, ensuring that the chosen site aligns with operational efficiency and long-term sustainability goals.

The application of the Fuzzy TOPSIS method allowed for a nuanced analysis of each potential site—Bình Dương, Long An, Đồng Nai, Vũng Tàu, and Bình Phước—by handling the inherent uncertainties and imprecisions associated with qualitative criteria. The results revealed that Đồng Nai emerged as the highest-ranking site, demonstrating strong performance across crucial sustainability factors, including environmental impact, economic viability, and social considerations. The Fuzzy TOPSIS analysis highlighted Đồng Nai's superior alignment with the ideal sustainability criteria, suggesting it as the most suitable location for new manufacturing facilities.

Subsequently, the VIKOR method refined the decision-making process by determining the best compromise solution. This method, which balances group utility and individual regret, confirmed the findings of the Fuzzy

TOPSIS analysis. Đồng Nai remained the top choice, followed by Bình Dương and Vũng Tàu, with Long An and Bình Phước ranking lower due to specific challenges related to cost and regulatory factors.

The results underscore the importance of adopting a multi-criteria decision-making framework incorporating sustainability aspects into site selection. By integrating both Fuzzy TOPSIS and VIKOR methods, this study provides a robust and comprehensive evaluation of potential sites, considering both quantitative and qualitative factors. The findings offer valuable insights for decision-makers, guiding them in selecting sites that meet immediate operational needs and contribute to long-term sustainability objectives.

However, the study has limitations. The reliance on static criteria and data constraints may affect the accuracy and applicability of the results. Future research could benefit from incorporating dynamic factors, such as economic shifts and technological advancements, and engaging with local stakeholders to refine criteria and weights. Additionally, real-time data and broader stakeholder input could enhance the robustness of the decision-making framework.

In short, the hybrid Fuzzy TOPSIS and VIKOR approach provides a comprehensive and effective method for integrating sustainability criteria into manufacturing plant site selection. The study's findings highlight Đồng Nai as the most favorable site, offering a balanced combination of sustainability and operational benefits. This research contributes to sustainable site selection and provides a valuable framework that can be adapted and applied in various industrial contexts. In further studies, we will use different methods to support decision-making in practical cases and compare them with previous studies as presented by Nguyen (2022), Wang (2023), and Wang (2024).

Scientific Ethics Declaration

The authors declare that the scientific, ethical, and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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