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A Soft Computing–Based Decision Support Framework Integrating GIS, FAHP, WLC, and TOPSIS for Sustainable Solid Waste Management Planning

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ABSTRACT

The proposed decision framework adopts a deliberately modular structure in which criterion weighting, spatial modelling, and alternative ranking are treated as independent analytical stages, thereby eliminating functional redundancy and reducing computational uncertainty. Uncertainty in expert judgment is addressed solely during the weighting phase through the application of the Fuzzy Analytic Hierarchy Process, ensuring that ambiguity does not propagate into subsequent spatial analyses. Spatial suitability is then modeled using a constrained Weighted Linear Combination approach that produces a continuous surface reflecting ecological and planning limitations. Rather than ranking individual grid cells, final prioritization is conducted at the decision-support level using the Technique for Order Preference by Similarity to Ideal Solution, where candidate locations are assessed as discrete, implementable planning entities. To safeguard the integrity of the results, sensitivity testing is intentionally restricted to the final ranking stage, preventing distortion of the spatial evaluation process. The framework is demonstrated using municipality-scale data, confirming its potential as a transparent, replicable, and technology-oriented decision support approach for solid waste management planning. A case-based implementation using municipal-scale spatial data is included to demonstrate the practical applicability and robustness of the proposed framework.

Keywords: Decision Support System, Soft Computing, Fuzzy AHP, GIS-Based Analysis, TOPSIS, Weighted Linear Combination, Solid Waste Management, Sensitivity Analysis

INTRODUCTION

The growing intricacy of urban solid waste management has rendered landfill site selection a complex, multi-dimensional decision process characterized by spatial variability, competing objectives, and uncertainty in expert assessments [1]. Conventional planning methods, which typically depend on single-criterion analysis or rigid rule-based screening, fail to adequately represent the multidimensional and computational nature of this challenge. Consequently, decision support systems (DSS) that combine geospatial information with advanced multi-criteria decision-making methods have gained prominence as reliable instruments for facilitating transparent and justifiable planning outcomes. In this regard, the coupling of Geographic Information Systems (GIS) with algorithm-driven decision models provides a coherent computational environment for systematically managing spatial constraints, diverse evaluation criteria, and stakeholder preferences.

Although GIS-based multi-criteria decision analysis has been widely applied to landfill site selection, many existing studies continue to rely on crisp weighting methods and raster-level optimization, limiting their ability to represent uncertainty and realistic decision processes [2]. Conventional implementations of the Analytic Hierarchy Process (AHP) assume precise pairwise judgments, even though expert evaluations in environmental planning are often vague and linguistically expressed. Moreover, spatial decision models frequently treat pixel-

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level suitability values as final decisions, overlooking the distinction between spatial assessment and implementable planning alternatives. These simplifications reduce the effectiveness of GIS-based decision support systems in complex urban infrastructure planning contexts.

To overcome these limitations, this study proposes a methodologically decoupled decision support framework in which each computational stage performs a clearly defined and non-overlapping function [3]. Uncertainty in expert judgment is addressed solely through the Fuzzy Analytic Hierarchy Process (FAHP), allowing criteria weights to reflect inherent human imprecision rather than deterministic assumptions. Spatial suitability is modeled independently using Weighted Linear Combination (WLC) to generate a continuous surface under explicit ecological constraints, while final prioritization is conducted at the DSS level using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), where alternatives are assessed as implementable planning units instead of raster cells. This strict separation of weighting, aggregation, and ranking improves transparency, avoids methodological ambiguity, and conforms to established decision support system design principles. Additionally, a case-based implementation is presented to validate the operational applicability of the proposed framework in a real-world municipal context.

Related Work and Research Gaps

GIS-based landfill site selection has been extensively studied using multi-criteria decision analysis to integrate spatial constraints with planning objectives. Early computational frameworks largely relied on overlay-based suitability mapping, combining environmental and infrastructural factors through weighted aggregation within GIS environments. Although these approaches highlighted the benefits of spatial decision support, they typically treated criteria weights as fixed values and interpreted raster-level suitability scores as final measures of site feasibility. From a computer science standpoint, such implementations provide limited capability for uncertainty handling, decision abstraction, and algorithmic modularity—key requirements for scalable and reusable decision support systems [4].

To address the limitations of crisp weighting, fuzzy set theory has been widely integrated into multi-criteria decision-making models for spatial planning applications. In particular, fuzzy extensions of the Analytic Hierarchy Process have been used to capture linguistic judgments and partial preferences in criteria weighting for landfill site selection. Although these approaches improve uncertainty representation at the weighting stage, many studies still embed FAHP within spatial aggregation or treat fuzzy raster-based suitability outputs as final decisions. This practice obscures the separation between preference modelling and decision execution, thereby reducing the effectiveness of such approaches as comprehensive decision support systems from a computational perspective [5].

Beyond fuzzy weighting methods, several studies have applied ranking-based multi-criteria techniques, such as the Technique for Order Preference by Similarity to Ideal Solution, to prioritize landfill sites and other infrastructure alternatives. These methods are typically implemented after spatial suitability mapping to rank candidate locations using aggregated scores. However, many existing applications either apply TOPSIS directly to raster-derived values or lack a clear decision abstraction, producing rankings with limited operational relevance for planners. From a decision support system perspective, this conflation of spatial evaluation and decision execution reduces model interpretability and reusability, highlighting the continued absence of a clear separation between spatial aggregation and alternative-level ranking in GIS-based soft computing applications [6].

Proposed Methodological Framework

The proposed decision support framework adopts a modular, multi-stage computational architecture that integrates geospatial analysis with soft computing–based decision modeling. It follows a sequential workflow in which data preparation, criteria weighting, spatial aggregation, alternative-level ranking, and robustness validation are implemented as independent yet interoperable components. From a computer science perspective, this modular design improves transparency, reproducibility, and scalability while avoiding functional overlap between analytical stages. By clearly separating uncertainty modeling, spatial evaluation, and decision

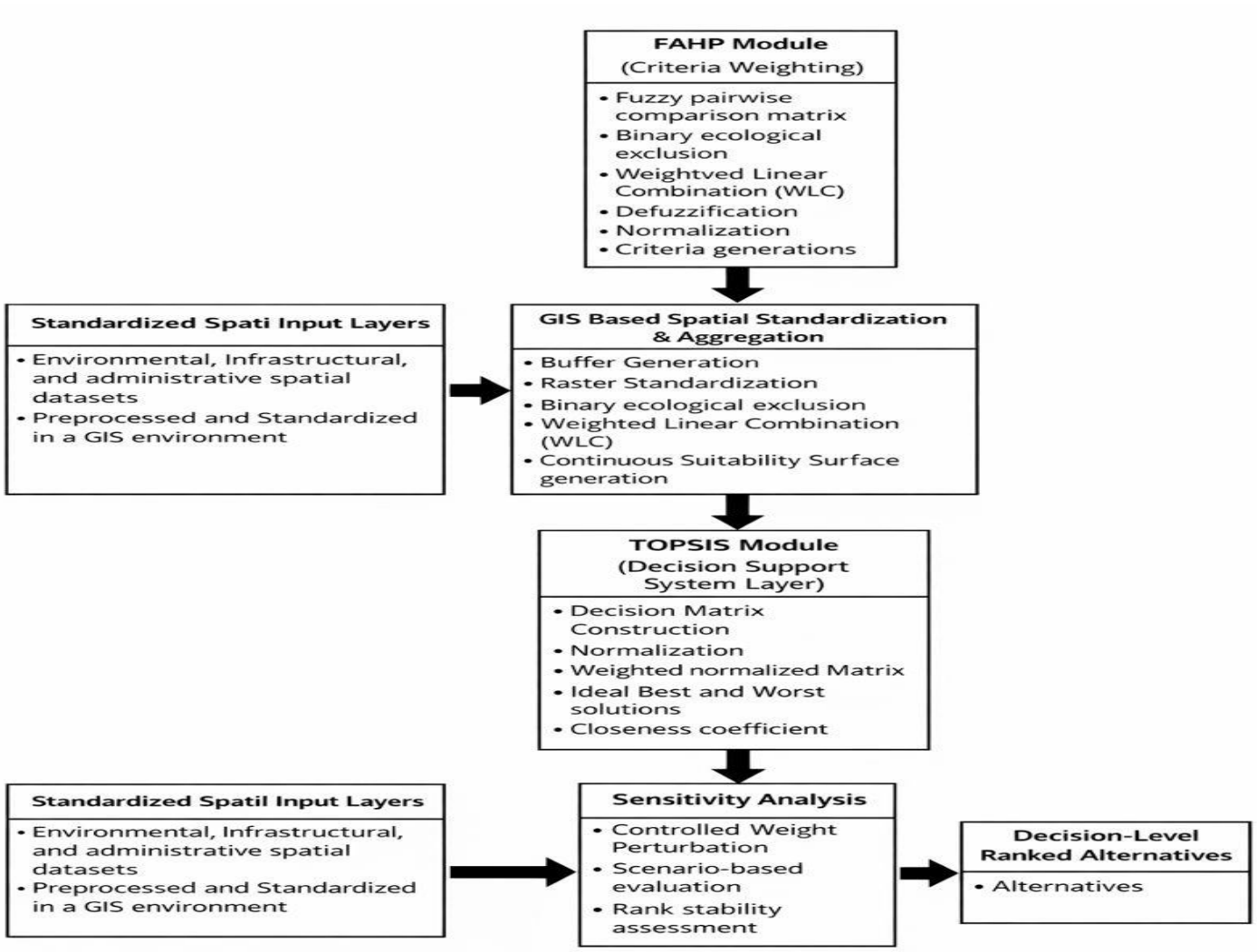
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execution, the framework ensures that each method operates within its defined role, supporting reliable and interpretable decision outcomes in complex planning contexts [7].

In the initial stage of the framework, spatial datasets representing environmental, infrastructural, and administrative factors are processed within a GIS environment to ensure consistency in coordinate systems, spatial resolution, and analytical extent. Distance-based constraints are converted into standardized suitability layers, while non-negotiable ecological constraints are applied through binary exclusion masks. This stage is strictly limited to spatial preprocessing and suitability representation, with no weighting or ranking logic introduced. From a computational perspective, separating spatial standardization from decision modelling prevents bias propagation and ensures that subsequent stages operate on validated, analysis-ready inputs rather than inconsistently processed data.

As illustrated in Fig. 1, decision modeling begins with a dedicated criteria weighting stage implemented using the Fuzzy Analytic Hierarchy Process (FAHP). This stage is intentionally separated from spatial aggregation and decision ranking so that uncertainty handling remains confined to preference elicitation and is not propagated to later computational steps. Expert judgments are expressed linguistically and represented using fuzzy numbers to capture the inherent vagueness of environmental and infrastructural criteria. By restricting FAHP exclusively to weight derivation, the proposed DSS avoids methodological coupling and maintains clear interpretability of both spatial and decision-level outputs.

Figure 1. - Modular Architecture of the proposed GIS-Based Soft computing Decision Support framework



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Algorithmic Workflow of the Proposed Framework

Step 1: GIS-based preparation and standardization of spatial datasets

Step 2: Derivation of criteria weights using FAHP under uncertainty

Step 3: Spatial aggregation using Weighted Linear Combination (WLC)

Step 4: Extraction of feasible decision alternatives from suitability surface

Step 5: Ranking of alternatives using TOPSIS

Step 6: Post-decision sensitivity analysis for robustness validation

This structured workflow ensures strict separation between analytical stages and improves transparency, reproducibility, and computational efficiency.

After criteria weights are obtained using FAHP, they are incorporated into the GIS-based spatial evaluation stage of the framework. At this stage, all thematic layers are standardized to a common suitability scale using distance- or rule-based methods, while ecologically non-negotiable constraints are enforced through binary exclusion masks. The normalized FAHP weights are then applied solely within a Weighted Linear Combination (WLC) scheme to generate a continuous spatial suitability surface. This aggregation step remains purely spatial and evaluative, producing a suitability index without performing discrete decision-making. By restricting FAHP weights to WLC-based aggregation, the framework preserves a clear separation between preference modeling and decision ranking, thereby avoiding methodological overlap and ensuring computational clarity.

Final decision-making in the proposed framework is handled by a TOPSIS-based decision support layer that operates exclusively on spatially aggregated outputs rather than individual raster cells. At this stage, the continuous suitability surface produced through WLC is translated into representative measures for a finite set of decision alternatives, thereby shifting the analysis from spatial evaluation to implementable planning decisions. TOPSIS ranks these alternatives based on their relative closeness to ideal and anti-ideal solutions, providing a transparent decision logic. By restricting TOPSIS to alternative-level ranking and excluding it from spatial aggregation or weight derivation, the framework maintains a clear separation between evaluation and decision execution, a key requirement of robust decision support system design.

To evaluate the robustness of decision outcomes, the framework incorporates sensitivity analysis as a dedicated post-decision validation stage. Unlike conventional approaches that recomputed spatial aggregation under multiple scenarios, sensitivity analysis is conducted strictly at the decision support system level by perturbing selected criteria weights while preserving all validated spatial layers and aggregation results. This approach assesses the stability of decision rankings without introducing spatial inconsistency or unnecessary recomputation. By confining sensitivity analysis to the final decision stage, the framework maintains methodological integrity, reduces computational redundancy, and provides transparent evidence of decision stability, thereby strengthening the reliability of the proposed DSS in complex planning contexts.

The criteria weighting component of the proposed framework is implemented using the Fuzzy Analytic Hierarchy Process (FAHP) to explicitly capture uncertainty and subjectivity in expert judgment. In complex spatial planning contexts, decision-makers often express preferences linguistically, which cannot be adequately represented by crisp weighting methods. FAHP overcomes this limitation by extending classical AHP with fuzzy set theory, allowing pairwise comparisons to be modeled using fuzzy numbers rather than precise ratios. Within the framework, FAHP is applied exclusively to derive relative criterion weights and is not involved in spatial aggregation or alternative ranking. This strict confinement localizes uncertainty handling to preference elicitation and preserves the interpretability and modularity of subsequent computational stages [8].

In the FAHP formulation used in this study, expert preferences among decision criteria are elicited through pairwise comparisons expressed in linguistic terms and represented using triangular fuzzy numbers (TFNs). This

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approach captures relative importance as value ranges rather than precise ratios, reflecting the inherent vagueness of human judgment in environmental and infrastructure planning. TFNs enable efficient arithmetic operations on fuzzy judgments while maintaining computational tractability. By organizing expert input into a fuzzy pairwise comparison matrix, the framework ensures consistent preference representation and supports robust fuzzy weight derivation without imposing unrealistic precision on decision-makers [9].

Following construction of the fuzzy pairwise comparison matrix, criteria weights are computed using the fuzzy synthetic extent method, which aggregates fuzzy judgments to estimate relative criterion importance. The method evaluates degrees of possibility among criteria to obtain a normalized priority vector. To ensure compatibility with subsequent computational stages, the fuzzy weights are defuzzified into crisp values while retaining the uncertainty captured during preference elicitation. The resulting normalized weights, satisfying the unity condition ($\Sigma w = 1$), are then transferred exclusively to the spatial aggregation module, completing the FAHP-based weighting process within the proposed framework [10].

To ensure the reliability of the derived criteria weights, the FAHP implementation incorporates consistency and normalization checks to maintain logical coherence in expert judgments. Although fuzzy modeling relaxes the strict consistency requirements of classical AHP, coherent pairwise comparisons remain essential for meaningful interpretation of weights. In the proposed framework, potential inconsistencies are controlled through structured linguistic scales and normalization of the defuzzified weight vector, ensuring stable and comparable importance values across criteria. By completing the FAHP stage with a validated and normalized weight set, the framework provides reliable input for spatial aggregation without requiring iterative recalibration, reinforcing the robustness and module

Spatial Aggregation Using Weighted Linear Combination (WLC)

Spatial aggregation in the proposed framework is performed using the Weighted Linear Combination (WLC) method, which serves as the sole mechanism for integrating standardized spatial criteria into a continuous suitability surface. WLC is well suited to spatial decision problems as it linearly combines multiple criteria while preserving their relative importance through externally derived weights. Within the framework, WLC operates exclusively on analysis-ready raster layers generated during GIS preprocessing and applies FAHP-derived normalized weights as fixed inputs. This separation ensures that spatial aggregation reflects evaluated preferences without introducing ranking or decision logic at the raster level. Consequently, WLC functions purely as a spatial evaluation tool, producing a composite suitability index that supports, but does not constitute, final decision-making [12].

Before aggregation, all spatial criteria are converted into a harmonized suitability framework to ensure compatibility within the WLC model. Distance- and rule-based factors are standardized to a common suitability scale, while ecologically or planning-wise non-negotiable constraints are enforced through binary exclusion masks rather than graded values. This explicit separation between factors and constraints prevents ambiguity in spatial evaluation by ensuring that prohibited areas are fully excluded rather than merely penalized. As a result, the framework preserves spatial realism and avoids misinterpreting infeasible locations as low-suitability options, thereby enhancing the integrity of the aggregated suitability surface [13].

Within the WLC formulation, standardized criterion suitability values are combined through weighted summation, with each criterion contributing according to its assigned importance. The resulting composite index provides a continuous representation of spatial suitability, allowing fine-grained differentiation across the study area without introducing discrete classification or ranking at this stage. WLC does not compare alternatives or identify optimal solutions; its function is limited to synthesizing spatial information into an evaluative surface. By confining WLC to continuous aggregation and excluding decision logic, the framework maintains a clear separation between suitability modeling and subsequent decision-support processes, thereby ensuring computational transparency and methodological rigor [14].

The continuous suitability surface produced through WLC is treated strictly as an evaluative representation of spatial favourability rather than a final site selection. No classification or threshold-based zoning is applied at

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this stage, as such operations can introduce subjective bias and unnecessarily restrict decision flexibility. Retaining the surface in continuous form preserves spatial detail and enables subsequent extraction of representative values for defined decision alternatives. By deferring all ranking and selection tasks to the dedicated decision support system layer, the framework maintains neutrality in spatial aggregation and enforces a clear separation between spatial evaluation and decision execution, thereby completing the WLC stage in a methodologically consistent manner [15].

The final decision-making stage of the framework employs the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) at the decision support system level rather than within the spatial domain. Unlike raster-based prioritization methods, TOPSIS is applied solely to a finite set of decision alternatives derived from spatial aggregation, ensuring that ranking is performed on implementable planning units. This abstraction enables a clear transition from continuous spatial evaluation to discrete decision analysis required for practical planning and policy formulation. By restricting TOPSIS to post-aggregation ranking, the framework maintains methodological clarity and avoids conflating spatial suitability modeling with decision execution [16].

DSS-Level Decision Modelling Using TOPSIS

The TOPSIS implementation is based on a decision matrix in which each alternative is evaluated using a consistent set of performance indicators derived from the spatial aggregation stage. These indicators summarize suitability values extracted from the continuous WLC surface, allowing TOPSIS to operate on spatially informed yet non-spatial data. The decision matrix is then normalized to remove scale effects and weighted using the FAHP-derived criteria weights, ensuring consistency between preference modeling and decision evaluation. Ideal best and worst solutions are subsequently identified as reference points for comparison, enabling transparent and computationally efficient ranking of alternatives without reintroducing uncertainty modeling or spatial aggregation at the decision stage [17].

The final ranking of decision alternatives in TOPSIS is obtained through the computation of the closeness coefficient, which quantifies the relative proximity of each alternative to the ideal best solution while simultaneously considering its distance from the ideal worst solution. This measure provides an intuitive and mathematically grounded basis for ranking, as higher closeness values indicate alternatives that better satisfy the weighted decision criteria. Within the proposed framework, the closeness coefficient serves solely as a decision indicator and is not fed back into spatial analysis or weight recalibration. By interpreting TOPSIS outcomes strictly as relative preference scores among predefined alternatives, the framework ensures that decision results remain transparent, comparable, and suitable for planning-level interpretation without altering any previously validated spatial or weighting components [18].

By restricting TOPSIS to the ranking of decision alternatives, the proposed framework preserves consistency and interpretability throughout the decision process. Ranking outcomes reflect relative preferences based on fixed criteria weights and spatially derived performance indicators, without introducing feedback loops or iterative recalculations. This design is critical for planning-oriented decision support systems, where stability and traceability of results are essential. By avoiding reweighting or spatial recomputation at the decision stage, the framework ensures a transparent audit trail from criteria evaluation to final ranking, thereby enhancing the credibility and practical usability of TOPSIS-based decisions in complex multi-criteria planning contexts [19]**.**

Robustness validation is a key element of decision support system design, as it examines the stability of decision outcomes under controlled parameter variations. In the proposed framework, sensitivity analysis is explicitly incorporated to evaluate the reliability of TOPSIS-based rankings produced by the integrated FAHP–WLC process. Rather than being used as an intermediate diagnostic step, sensitivity analysis is positioned as a formal post-decision validation mechanism. This design ensures that robustness assessment focuses on final decision outcomes, providing confidence that the rankings are not overly sensitive to marginal changes in criteria importance **[**20].

In the proposed framework, sensitivity analysis is conducted by systematically perturbing selected criteria weights while keeping all spatial layers, aggregation outputs, and decision alternatives unchanged. This strategy

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isolates the influence of preference uncertainty on decision outcomes without introducing effects from repeated spatial processing. Weight perturbations are applied within predefined bounds and re-normalized to satisfy the unity condition, after which TOPSIS rankings are re-evaluated. By confining sensitivity analysis to the decision stage and avoiding recomputation of FAHP weights or WLC surfaces, the framework maintains computational efficiency and methodological consistency, ensuring that robustness assessment reflects the stability of decision rankings rather than variability in intermediate model components [21].

The results of sensitivity analysis are interpreted in terms of rank stability and decision confidence rather than numerical variation alone. In the proposed framework, robustness is evaluated by examining whether the relative ordering of alternatives remains unchanged under weight perturbation scenarios, indicating stable decision outcomes. The absence of rank reversal provides strong evidence of resilience to moderate changes in expert preferences, while any instability can be directly linked to specific criteria perturbations for transparent diagnosis. By presenting robustness results as validation of decision consistency rather than optimization, the framework strengthens the credibility of TOPSIS-based rankings and supports defensible decision-making in complex multi-criteria environments [22].

Case-Based Implementation

A municipal-scale case study was used to test the proposed framework using spatial datasets such as land use, transport infrastructure, environmental restrictions, and terrain. All layers were processed in a GIS environment and converted into a unified suitability scheme, with ecologically sensitive zones excluded from consideration.

Weights were estimated through the Fuzzy Analytic Hierarchy Process (FAHP) to reflect uncertainty in expert input, and then applied in a Weighted Linear Combination (WLC) to produce a Landfill Suitability Index (LSI) map. Potential sites identified from the LSI were treated as decision alternatives and ranked using TOPSIS, enabling systematic prioritization.

The results show clear separation among candidate sites and illustrate how the framework supports transparent, data-driven landfill site selection by combining geospatial analysis with soft computing methods.

Comparative Perspective with Conventional GIS–MCDA Approaches

Aspect	Conventional AHP-Based GIS Models	Proposed Framework
Weighting	Crisp AHP	FAHP (uncertainty-aware)
Spatial Aggregation	Direct overlay	WLC (structured aggregation)
Decision Ranking	Often implicit or absent	Explicit TOPSIS ranking
Method Integration	Overlapping stages	Strict modular separation
Uncertainty Handling	Limited	Explicitly incorporated
Transparency	Moderate	High

The comparison highlights that the proposed framework improves methodological clarity, enhances uncertainty handling, and provides a more structured and transparent decision-making process compared to traditional GIS-based MCDA approaches.

DISCUSSION

Computational and DSS Implications.

The proposed GIS-integrated soft computing framework exhibits key computational and decision support system (DSS) advantages over conventional spatial multi-criteria approaches. From a computational perspective, the strict separation of criteria weighting, spatial aggregation, decision ranking, and robustness validation minimizes algorithmic coupling and improves model transparency. Each module operates on clearly defined inputs and generates outputs that feed subsequent stages without feedback interference. This modular structure simplifies implementation, enhances reproducibility and scalability, and allows adaptation to diverse planning contexts

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without structural changes. By aligning the computational workflow with DSS design principles, the framework enables traceable and auditable decision processes, which are essential for reliable decision support systems.

Compared with tightly coupled GIS–MCDA implementations, the proposed framework provides clear advantages in decision transparency and robustness. In many existing models, weighting, aggregation, and ranking are intertwined, making it difficult to trace how individual criteria influence final outcomes. In contrast, the modular structure adopted here allows each analytical stage to be independently examined, validated, and adjusted without cascading effects. This transparency is particularly valuable in multi-stakeholder decision support environments where justification is as critical as the decision itself. Moreover, separating spatial evaluation from decision execution ensures that robustness assessments reflect true decision sensitivity rather than artefacts of repeated spatial recomputation, thereby strengthening confidence in the resulting rankings.

The proposed framework also exhibits strong computational efficiency and scalability, which are essential for technology-driven decision support systems. By eliminating iterative recomputation of spatial layers during weighting, ranking, and sensitivity analysis, the framework reduces redundant processing and overall computational cost. This efficiency enables application to large-scale spatial datasets and supports use in resource-constrained computational environments. In addition, the modular architecture facilitates integration with scripting and automation tools, allowing seamless implementation within modern GIS and data analytics platforms. Consequently, the framework supports scalable DSS deployment while maintaining methodological rigor, making it well suited for complex, data-intensive planning applications.

Beyond computational efficiency, the proposed framework demonstrates strong generalizability and transferability, which are essential attributes of decision support systems developed from a computer science perspective. Defined by modular analytical roles rather than application-specific heuristics, the framework can be readily adapted to other infrastructure planning problems involving spatial evaluation, multi-criteria preference modeling, and decision-level ranking. The clear abstraction between spatial processing and decision execution allows domain-specific criteria and constraints to be incorporated without modifying the underlying DSS architecture. This flexibility positions the framework as a reusable decision support template rather than a one-off application, enhancing its relevance for technology-driven planning and management contexts that require transparency, robustness, and computational rigor.

The case-based implementation further demonstrates that the proposed framework produces stable and interpretable decision outcomes. The modular separation of FAHP, WLC, and TOPSIS ensures that uncertainty handling, spatial evaluation, and decision ranking remain independent, thereby improving both computational efficiency and decision transparency compared to conventional integrated approaches.

CONCLUSION

This study presents a soft computing–based decision support framework that integrates GIS, FAHP, WLC, TOPSIS, and sensitivity analysis within a strictly modular and computationally disciplined architecture. By enforcing a clear separation between criteria weighting, spatial aggregation, decision ranking, and robustness validation, the framework overcomes key methodological limitations of tightly coupled GIS–MCDA approaches. FAHP is confined to uncertainty-aware weight derivation, WLC to continuous spatial evaluation, TOPSIS to alternative-level decision ranking, and sensitivity analysis to post-decision validation. This structured design enhances transparency, reproducibility, and robustness while avoiding unnecessary recomputation of validated spatial layers. From a computer science perspective, the framework functions as a reusable DSS architecture adaptable to diverse spatial planning problems, providing a strong foundation for technology-driven decision support in complex planning environments.

Beyond methodological rigor, the proposed framework provides a practical pathway toward an automated and transferable decision support solution for municipal solid waste management. By organizing the decision process into modular and clearly defined computational stages, the framework can be readily adapted by municipal authorities with differing data availability, regulatory conditions, and planning priorities. Each module—criteria weighting, spatial evaluation, decision ranking, and robustness validation—can be implemented as an

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independent computational service, enabling seamless integration within modern GIS and data-driven planning environments. Within the broader context of AI-enabled and smart city systems, the framework supports automation through scripting, rule-based updates, and expert-in-the-loop decision modeling, thereby reducing reliance on ad hoc manual analysis. Consequently, the proposed DSS functions not only as a landfill siting approach but also as a scalable and operational decision-support blueprint for sustainable municipal solid waste management planning.

The inclusion of a case-based implementation confirms the operational feasibility of the framework in real-world municipal planning contexts. The proposed approach provides a scalable foundation for future integration with automated and AI-assisted decision support systems.

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