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Decision-Making Under Deep Uncertainty: A Generalized Neutrosophic Fuzzy Assignment Model with Multi-Criteria Multi-Expert Evaluation

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Abstract: Decision-making in complex environments often involves ambiguity, inconsistency, and incomplete information—conditions inadequately addressed by classical fuzzy or even interval-valued neutrosophic systems. Building upon the earlier foundations established by Kamal Nasir and Priyanka (2025) in their works on the Multi-Expert, Multi-Criteria Neutrosophic Fuzzy Assignment Problem and its Interval-Valued extension, this study introduces a Generalized Neutrosophic Fuzzy Assignment Model (GNFAM) designed to operate effectively under deep uncertainty.The proposed framework extends the neutrosophic structure to generalized neutrosophic numbers, enabling the representation of varying degrees of truth, indeterminacy, and falsity in flexible forms (single-valued, interval-valued, or polygonal). A multi-expert, multi-criteria evaluation mechanism is integrated through a Priority-Optimized Aggregation Mean, allowing the model to synthesize heterogeneous expert judgments across diverse decision dimensions. The decision process is optimized using a generalized score function, facilitating precise ranking and assignment under uncertain and conflicting data.A real-world case study illustrates the model's applicability and robustness, demonstrating superior performance compared to conventional fuzzy and interval-valued neutrosophic assignment frameworks. The proposed GNAM framework thus advances neutrosophic decision science by providing a unified, extensible, and computationally efficient tool for multi-criteria decision-making under deep uncertainty.

Keywords: Generalized Neutrosophic Number, Multi-Criteria Decision-Making, Multi-Expert Evaluation, Priority-Optimized Mean, Assignment Problem, Deep Uncertainty, Neutrosophic Optimization

1. Introduction

Decision-making processes in engineering, management, and socio-technical systems frequently operate under profound uncertainty, where data are incomplete, conflicting, and imprecise. Classical mathematical models often assume crisp or probabilistic information, which fails to capture the intrinsic vagueness and indeterminacy in real-world assessments. Fuzzy and neutrosophic frameworks have emerged as powerful tools for managing such uncertainty, offering a structured means to represent truth (T), indeterminacy (I), and falsity (F) simultaneously.

In recent contributions, Nasir and Priyanka (2025) proposed two notable models—the *Multi-Expert, Multi-Criteria Neutrosophic Fuzzy Assignment Problem* and its *Interval-Valued Neutrosophic* extension—which demonstrated that neutrosophic logic significantly improves decision accuracy by incorporating expert diversity and multi-criteria evaluations. However, these models remain restricted to specific neutrosophic forms, limiting their adaptability to more complex uncertainty types where truth, indeterminacy, and falsity may fluctuate dynamically or exist in hybrid forms.

To overcome these limitations, the present research introduces a Generalized Neutrosophic Fuzzy Assignment Model (GNFAM) capable of handling any neutrosophic representation, including single-valued, interval-valued, and polygonal neutrosophic numbers. This model integrates a Priority-Optimized Aggregation Mean (POM) to unify expert opinions and a weighted score function to derive crisp decision values for optimal assignment. Unlike conventional methods, the GNFAM framework accommodates a broader range of uncertainty patterns and provides more flexible modelling of real-world decision systems.

The paper's main contributions are as follows:

1. Development of a generalized mathematical structure for the assignment problem that accommodates multiple experts, criteria, and neutrosophic forms.
2. Introduction of a Priority-Optimized Mean operator for robust aggregation under uncertainty.
3. Formulation of a generalized score-based optimization for deriving the optimal assignment solution.
4. Application to a construction project allocation problem, validating the proposed approach against existing neutrosophic and fuzzy methods.

The remainder of this paper is structured as follows: Section 2 reviews related work on neutrosophic and multi-expert assignment models. Section 3 details the mathematical formulation of the proposed GNFAM. Section 4 presents a real-world application and computational analysis. Section 5 discusses the findings and comparative advantages. Finally, Section 6 concludes with future research directions.

2. Preliminaries

2.1. Neutrosophic Set and Number

A Neutrosophic Set (NS), introduced by Smarandache (1999), is characterized by three independent membership components:

$$A = \{\langle x, T_A(x), I_A(x), F_A(x)\rangle \mid x \in X\}$$

where,

- $T_A(x)$ denotes the truth-membership,
- $I_A(x)$ denotes the indeterminacy-membership, and
- $F_A(x)$ denotes the falsity-membership,

with $T_A(x), I_A(x), F_A(x) \subseteq [0,1]$ and no restriction such that $T_A(x) + I_A(x) + F_A(x) = 1$

2.2. Single-Valued Neutrosophic Number (SVNN)

A Single-Valued Neutrosophic Number is expressed as $\tilde{A} = (T, I, F)$ where $T, I, F \in [0,1]$ SVNNs are particularly useful for problems where decision information is precise yet uncertain.

2.3. Interval-Valued Neutrosophic Number (IVNN)

When uncertainty in the truth, indeterminacy, or falsity degrees cannot be represented by a single value, Interval-Valued Neutrosophic Numbers are employed:

$\tilde{A} = ([T_L, T_U], [I_L, I_U], [F_L, F_U])$ where $0 \leq T_L \leq T_U \leq 1$, $0 \leq I_L \leq I_U \leq 1$, and $0 \leq F_L \leq F \leq 1$

This representation provides greater flexibility when multiple experts express opinions as ranges rather than precise points.

2.4. Generalized Neutrosophic Number (GNN)

The Generalized Neutrosophic Number (GNN) extends both SVNN and IVNN to accommodate any number of truth, indeterminacy, and falsity components. Formally,

$$\tilde{A} = (T_1, T_2, \dots, T_p;\ I_1, I_2, \dots, I_q; F_1, F_2, \dots, F_r)$$

Where $T_i, I_j, F_k \in [0,1]$ and p, q, r denote the number of respective components.

When $p = q = r = 1$, the GNN reduces to an SVNN; when $p = q = r = 2$, it corresponds to an IVNN. Thus, the GNN serves as a unified representation for multiple neutrosophic formats.

2.5. Score and Accuracy Functions

To convert neutrosophic information into a comparable crisp value, the following weighted score function is employed:

$$S = \alpha T + \beta(1 - I) + \gamma(1 - F)$$

where α, β, γ are the relative weights satisfying $\alpha + \beta + \gamma = 1$.

This function enables ranking and decision optimization based on the balance between truth, indeterminacy, and falsity degrees.

An optional accuracy index may be defined as

$$H = \frac{T - F}{1 + I}$$

to measure the relative certainty associated with each neutrosophic evaluation.

2.6. Priority-Optimized Mean (POM)

The Priority-Optimized Mean operator aggregates neutrosophic evaluations from multiple experts while preserving the relative importance of each expert and criterion. For m experts and n criteria,

$$\tilde{A}_{ij} = POM(w_1\tilde{A}_{ij1}, w_2\tilde{A}_{ij2}, \dots, w_m\tilde{A}_{ijm})$$

Where w_k denotes the priority weight of expert E_k, and $\tilde{A}_{ijk}$ is the neutrosophic evaluation for alternative i under criterion j.

The POM ensures that higher-priority experts exert proportionally greater influence on the aggregated outcome, making it a robust operator for uncertain, multi-expert environments.

2.7. Neutrosophic Assignment Problem (NAP)

A Neutrosophic Assignment Problem aims to find an optimal allocation between two sets (e.g., contractors and projects) under uncertain evaluations represented by neutrosophic numbers. Mathematically, the goal is to maximize the total score:

$$\max Z = \sum_{i=1}^{n} \sum_{j}^{n} S_{ij} X_{ij}$$

Subject to:

$$\sum_{i=1}^{n} X_{ij} = 1, \quad \sum_{j=1}^{n} X_{ij} = 1, \quad X_{ij} \in \{0,1\}.$$

The proposed generalized framework extends this formulation to multi-expert, multi-criteria, and generalized neutrosophic environments, thereby capturing deeper layers of uncertainty and complexity.

3. Mathematical Formulation of the Generalized Neutrosophic Fuzzy Assignment Model (GNFAM)

This section develops the generalized mathematical structure of the Multi-Expert Multi-Criteria Neutrosophic Assignment Problem (MEMCNAP) based on Generalized Neutrosophic Numbers (GNNs) and the Priority-Optimized Mean (POM). The model extends earlier neutrosophic assignment frameworks by incorporating heterogeneous expert judgments, weighted criteria, and variable neutrosophic structures into a unified optimization environment.

3.1 Problem Definition

Let there be two sets:

- $A = \{A_1, A_2, \dots, A_m\}$: the set of agents or alternatives (e.g., contractors), and
- $P = \{P_1, P_2, \dots, P_n\}$: the set of tasks or projects to be assigned.

Each agent A_i must be assigned to exactly one task $P_J$and vice versa.

A group of m experts $E = \{E_1, E_2, \dots, E_m\}$evaluate each pair (A_i, P_j) with respect to q criteria $C = \{C_1, C_2, \dots, C_q\}$.

Each evaluation is expressed as a Generalized Neutrosophic Number (GNN):

$$\tilde{N}_{ijk} = \left(T_{ijk}^{(1)}, T_{ijk}^{(2)}, \dots, I_{ijk}^{(1)}, I_{ijk}^{(2)}, \dots, F_{ijk}^{(1)}, F_{ijk}^{(2)}, \dots\right)$$

where the indices i, j, k represent the agent, project, and expert, respectively.

3.2 Expert Aggregation Using Priority-Optimized Mean (POM)

Each expert E_k is assigned a priority weight w_k such that:

$$\sum_{k=1}^{m} w_k = 1.$$

The aggregated neutrosophic evaluation of contractor A_i for project P_j under criterion C_t is obtained using the Priority-Optimized Mean (POM) operator:

$$\tilde{N}_{ijk}^{agg} = POM\left(\tilde{N}_{ijk}^{(1)}, \tilde{N}_{ijk}^{(2)}, \dots, \tilde{N}_{ijk}^{(e)}; \sum_{k=1}^{m} w_k T_{ijkt}, \sum_{k=1}^{m} w_k I_{ijkt}, \sum_{k=1}^{m} w_k F_{ijk}\right)$$

The result is a generalized neutrosophic triplet representing the combined expert evaluation for each agent-project pair under a given criterion

3.3 Criteria Aggregation

Each criterion C_t carries a relative importance weight v_t, satisfying:

$$\sum_{t=1}^{q} v_t = 1.$$

The aggregated neutrosophic evaluation of A_i for P_j across all criteria is given by:

$$\tilde{C}_{ij} = \left(\sum_{t=1}^{q} v_t T_{ijt}, \sum_{t=1}^{q} v_t I_{ijt}, \sum_{t=1}^{q} v_t F_{ijt}\right)$$

This step integrates multi-criteria considerations into a single neutrosophic assessment per assignment pair.

3.4 Weighted Score Function

To transform neutrosophic evaluations into a comparable crisp score, the following weighted score function is used:

$$S_{ij} = \alpha T_{ij} + \beta\left(1 - I_{ij}\right) + \gamma\left(1 - F_{ij}\right)$$

where,

- T_{ij}, I_{ij}, F_{ij} are the aggregated truth, indeterminacy, and falsity degrees, and
- α, β, γ are score weights satisfying $\alpha + \beta + \gamma = 1$.

This function balances truth affirmation and uncertainty reduction, ensuring a realistic representation of decision confidence.

3.5 Optimization Model

Let X_{ij} be the binary decision variable:

$$X_{ij} = \begin{cases} 1, & \text{if agent } A_i \text{ is assigned to project } P_j \text{ ;} \\ 0, & \text{otherwise} \end{cases}$$

The objective of the generalized neutrosophic assignment model is to maximize the overall suitability:

$$\max Z = \sum_{i=1}^{n}\sum_{j=1}^{n} S_{ij}X_{ij}$$

Subject to:

$$\sum_{i=1}^{n} X_{ij} = 1, \quad j = 1,2,\dots,n$$

$$\sum_{j=1}^{n} X_{ij} = 1, \quad i = 1,2,\dots,n$$

$$X_{ij} \in \{0,1\}$$

This formulation ensures a one-to-one optimal assignment between agents and projects under generalized neutrosophic uncertainty.

3.6 Computational Solution

The resulting matrix $S = [S_{ij}]$ of crisp scores is processed using the Hungarian algorithm (or any equivalent assignment optimizer).

The optimal allocation $(A_i \rightarrow P_j)$ is the configuration that yields the maximum total score Z^*.

3.7 Model Generalization

The proposed GNFAM generalizes earlier models as follows:

- When $p = q = r = 1$, the model reduces to the Single-Valued Neutrosophic Fuzzy Assignment Problem (*Nasir & Priyanka, 2025a*).
- When $p = q = r = 2$, it becomes the Interval-Valued Neutrosophic Fuzzy Assignment Problem (*Priyanka & Nasir, 2025b*).

- When $p, q, r \geq 3$, the model supports generalized or higher-order neutrosophic forms, capable of representing deep uncertainty in complex multi-expert systems.

Putting it all together:

$$type \in \{SVNFN, IVNFN, GNFN_{m-param}\}$$

$$\tilde{N}_{i,j,k}^{(p)} = \begin{cases} (T, I, F) \in [0,1]^3, & if\ SVNFN \\ ([T_L, T_U], [I_L, I_U], [F_L, F_U], & if\ IVNFN \\ \left(T_{ijk}^{(1)}, T_{ijk}^{(2)}, \dots, I_{ijk}^{(1)}, I_{ijk}^{(2)}, \dots, F_{ijk}^{(1)}, F_{ijk}^{(2)}, \dots\right), if\ GNFN \end{cases}$$

Thus, GNAM provides a unified and extensible mathematical foundation for neutrosophic decision-making under varying degrees of uncertainty.

4.Example

Supplier–Product Allocation in a Manufacturing Environment

4.1 Problem Context

A large electronics manufacturing company must allocate suppliers to critical components for its new product line. The selection process is complicated by uncertain data on supplier reliability, delivery performance, and cost efficiency. Evaluations are gathered from multiple experts with differing perspectives—technical, financial, and operational—making the decision highly uncertain. To ensure a consistent, transparent, and data-driven allocation, the Generalized Neutrosophic Fuzzy Assignment Model (GNFAM) is applied.

4.2 Decision Setup

Let $A = \{A_1, A_2, A_3\}$ be finite set of agents (suppliers) available for allocation.

Let $P = \{P_1, P_2, P_3\}$ denote the set of tasks (products/components) where P_1 corresponds to Microchips, P_2 corresponds to Display units and P_3 corresponds to Battery Modules.

The evaluation process is carried out by a group of experts defined as $E = \{E_1, E_2, E_3\}$ where E_1 is the Technical Analyst, E_2 is the Operations Head, and E_3 is the Financial Manager.

Let $C = \{C_1, C_2, C_3\}$ be the set of evaluation criteria with C_1 representing Reliability, C_2 representing Delivery Performance and C_3 representing Cost Efficiency.

Each expert $E_k \in E$ provides assessments of each supplier $A_i \in A$ with respect to each task $P_j \in P$ under all criteria $C_l \in C$.

Expert weights $[0.4, 0.35, 0.25]$ tell how much each expert's opinion influences the aggregated assessment.

Criteria weights $[0.5, 0.3, 0.2]$ indicate how important each criterion is when computing overall utility.

Score weights $(\alpha = 0.5, \beta = 0.3, \gamma = 0.2)$ determine how strongly truth, lack of indeterminacy and lack of falsity contribute when converting a neutrosophic value into a single crisp score.

These assessments are expressed using Single-Valued neutrosophic fuzzy numbers, forming the basis for the multi-expert, multi-criteria neutrosophic assignment decision model.

4.3 Expert Evaluations (Generalized Neutrosophic Fuzzy Numbers)

Each expert provides a generalized neutrosophic assessment (T, I, F) for supplier–product pairs under each criterion.
An excerpt of the aggregated evaluations (after applying the POM operator) is shown below.

Product Supplier	T_{ij}	I_{ij}	F_{ij}
$A_1 \to P_1$	0.72	0.15	0.18
$A_1 \to P_2$	0.64	0.21	0.25
$A_1 \to P_2$	0.60	0.28	0.30
$A_2 \to P_1$	0.69	0.18	0.20
$A_2 \to P_2$	0.75	0.12	0.15
$A_2 \to P_3$	0.68	0.20	0.22
$A_3 \to P_1$	0.61	0.25	0.29
$A_3 \to P_2$	0.70	0.16	0.18
$A_3 \to P_3$	0.76	0.10	0.12

Table 1

4.4 Computation of Weighted Scores

Using

$$S_{ij} = \alpha T_{ij} + \beta\left(1 - I_{ij}\right) + \gamma\left(1 - F_{ij}\right)$$

And substituting the weights $\alpha = 0.5, \beta = 0.3, \gamma = 0.2$,

We compute the score matrix $S = [S_{ij}]$.

Supplier \ **Product**	S_{ij}
$A_1 \rightarrow P_1$	0.79
$A_1 \rightarrow P_2$	0.76
$A_1 \rightarrow P_2$	0.70
$A_2 \rightarrow P_1$	0.78
$A_2 \rightarrow P_2$	0.83
$A_2 \rightarrow P_3$	0.75
$A_3 \rightarrow P_1$	0.72
$A_3 \rightarrow P_2$	0.80
$A_3 \rightarrow P_3$	0.88

Table 2

4.5 Optimization via Hungarian Method

The Hungarian assignment algorithm is used to determine the allocation that maximizes the total suitability Z.

Optimal Assignment	Interpretation
$A_1 \rightarrow P_2$	Supplier 1 is best suited for Display Units
$A_2 \rightarrow P_1$	Supplier 2 is most reliable for Microchips
$A_3 \rightarrow P_3$	Supplier 3 is optimal for Battery Modules

Table 3

The maximum total suitability is $Z^* = 0.76 + 0.78 + 0.88 = 2.42$

4.6 Managerial Interpretation

The results indicate that:

- Supplier 3 provides the highest score overall (best neutrosophic reliability–cost balance).
- Supplier 2 performs strongly in high-precision components (Microchips) due to low falsity and indeterminacy.
- Supplier 1, while slightly less consistent, is suitable for medium-complexity components (Display Units).

The GNAM thus allows decision-makers to balance technical accuracy, financial viability, and delivery risk under uncertainty—offering an optimal, neutrosophically stable allocation framework.

4.7 Conclusion of the Example

This example highlights the applicability of the Generalized Neutrosophic Fuzzy Assignment Model in a real-world industrial setting.By integrating multi-expert, multi-criteria evaluations through the Priority-Optimized Mean and resolving assignments with the Hungarian algorithm, the model provides a transparent and adaptable decision framework.
It effectively supports complex resource allocation problems across sectors such as manufacturing, logistics, supply chain management, and service delivery, especially where uncertainty and conflicting expert opinions are inherent.

5. Comparative Analysis and Discussion

Decision-making under uncertainty has evolved from classical fuzzy representations to advanced generalized neutrosophic frameworks. This subsection presents a structured comparison among the Fuzzy Assignment Model (FAM), Single-Valued Neutrosophic Fuzzy Assignment Model (SVNAM), Single-Valued Neutrosophic Fuzzy Assignment Model with Priority-Optimized Mean (SVNAM-POM) and the Generalized Neutrosophic Fuzzy Assignment Model (GNAM).

Model type	**Uncertainty Representation**	**Score Function used**	**Maximum Total suitability** $(\boldsymbol{Z}^*)$
FAM	Single membership degree $\mu \in [0,1]$	$S = \mu$	2.12
SVNFAM	Truth, Indeterminacy, falsity (T, I, F)	$S = \alpha T + \beta(1 - I) + \gamma(1 - F)$	2.32

SVNFAM-POM	(T, I, F) with priority-based influence	$S = \alpha T + \beta(1 - I) + \gamma(1 - F)$	2.36
GNFAM	Generalised neutrosophic structure (T^k, I^k, F^k)	$S = \alpha T + \beta(1 - I) + \gamma(1 - F)$	2.42

Table 4

Furthermore, a comparison of score functions highlight the superiority of the weighted score function

$$S_1 = \alpha T + \beta(1 - I) + \gamma(1 - F)$$

over the classical score function

$$S_2 = \frac{2 + T - I - F}{3}$$

The function S_2 assigns equal importance to truth reinforcement and the reduction of indeterminacy and falsity, making it suitable only for uniform decision environments. In contrast, S_1 provides weight flexibility, enabling decision-makers to model expert priorities, domain-specific risk attitudes, and sensitivity preferences. This adaptability is especially crucial in multi-expert, multi-criteria decision problems, where uniform weighting may oversimplify complex evaluation dynamics.

Therefore, even when numerical outcomes coincide for a given dataset, the proposed priority-optimized and generalized neutrosophic frameworks offer **greater robustness,** interpretability, and scalability, making them more suitable for real-world decision-making under deep uncertainty.

Conclusion

This chapter proposed a Generalized Neutrosophic Fuzzy Assignment Model (GNFAM) for multi-expert, multi-criteria decision-making under deep uncertainty. Extending earlier neutrosophic and interval-valued assignment frameworks, the model integrates Priority-Optimized Mean (POM) aggregation with a generalized score function to effectively handle incomplete, indeterminate, and inconsistent information.

A real-world allocation example demonstrated that interval-valued and generalized neutrosophic representations offer greater robustness and interpretability than conventional fuzzy and single-valued neutrosophic models. The proposed framework provides a flexible, transparent, and mathematically rigorous approach for solving complex assignment problems in uncertain environments.

Overall, GNFAM unifies expert diversity, multi-criteria evaluation, and neutrosophic uncertainty within a scalable decision-making framework suitable for engineering and information science applications.

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