A Neutrosophic Framework for Multilevel Corruption Assessment in Central Asian Societies

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Abstract

We introduce a neutrosophic framework to assess corruption across micro, meso, and macro levels and illustrate it with a public, fully synthetic dataset covering five Central Asian societies (2020–2025). The framework models the proposition "High Corruption" with three independent degrees: Truth (T), Indeterminacy (I), and Falsity (F), which need not sum to one. We propose a summary index—the Neutrosophic Evidence Risk Index (NERI)—that couples evidence for and against high corruption with indeterminacy. Empirically, we document three stylized patterns in the synthetic data: (i) a moderate decline in country-level NERI over time for most countries; (ii) a negative association between region-year e-service adoption and bribe solicitation; and (iii) a negative association between digital government capacity and T at the country-year level. For example, the average bribe-solicitation rate is 0.047 overall, 0.198 without e-services (95% CI 0.175–0.220) vs. 0.019 with e-services (95% CI 0.015–0.022), implying a risk difference of -0.179 and a relative risk of 0.094.

Keywords: Neutrosophic Sets; Neutrosophic Logic; Indeterminacy; Uncertainty Quantification; Multilevel Modeling; Corruption Assessment; Governance; Central Asia; Public Sector Integrity; E-Government; Decision Support Systems; Transition Economies; Social Measurement; Institutional Analysis; Neutrosophic Sociology

1 Introduction

Corruption remains one of the most persistent and context-dependent challenges in public governance, especially in societies undergoing rapid institutional and economic transition. In Central Asia, the legacies of centrally planned systems, evolving legal frameworks, and varying degrees of administrative digitalization have created a complex landscape for integrity measurement and reform.[2,18,19] Conventional approaches to corruption assessment often rely on perception-based indices or single-level surveys, which inadequately capture the multilevel and uncertain nature of corruption phenomena.

The limitations of such deterministic or probabilistic models call for analytic frameworks that can explicitly accommodate ambiguity, contradiction, and partial truth. Neutrosophic logic, introduced by Smarandache[15] and further advanced across various social and engineering domains,[14,16] provides a mathematical structure to represent three independent components of information: truth (T), indeterminacy (I), and falsity (F). This triadic representation allows the coexistence of multiple, even conflicting, evidential states—an essential feature when analyzing corruption, where official data, social perception, and institutional behavior often diverge.

Neutrosophic frameworks have been applied successfully in modeling complex social systems where human judgment, institutional uncertainty, and contextual variation coexist. For example, neutrosophic sociology has been employed to study corruption in public procurement under crisis conditions[1] and to analyze systemic equity within justice systems.[4] Similarly, neutrosophic cognitive maps have been used to interpret interlinked social determinants such as crime, poverty, and governance,[3] highlighting the method's capacity to integrate uncertain qualitative data into formal reasoning models.

Beyond social analysis, neutrosophic approaches have gained traction in performance evaluation, risk modeling, and decision sciences.[5,6,13,21] They enable flexible representation of human-centered uncertainty in domains as diverse as industrial safety,[6] economic assessment,[20] and multi-criteria decision support.[13] Recent applications in statistical modeling[7,8,10,12] further demonstrate that neutrosophic statistics can generalize classical inference techniques to data characterized by imprecision, missingness, or cognitive inconsistency—features that mirror the realities of corruption data in transitional governance contexts.

Building on these theoretical and methodological advances, this study proposes a *neutrosophic multilevel framework* for corruption assessment in Central Asian societies. The framework models corruption not as a single observable index but as a layered construct measurable through micro-level interactions, meso-level institutional contexts, and macro-level governance indicators. By assigning independent neutrosophic degrees (T, I, F) to the proposition "High Corruption," we enable a more nuanced interpretation of mixed or conflicting signals in social and administrative data.

To demonstrate the framework's practical feasibility, we develop and analyze a fully synthetic dataset covering five Central Asian countries—Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan—across 2020–2025. This dataset mirrors real-world variability in digital governance, public trust, and policy implementation, while preserving the ethical advantage of non-identifiable, reproducible data. Through this design, we bridge the methodological rigor of neutrosophic modeling with the policy relevance of regional corruption analysis, offering a structured pathway toward uncertainty-aware integrity assessment.[2,18,19]

2 Related Background

Classical logic operates on binary truth values—true or false—offering limited expressive power in representing uncertain, incomplete, or contradictory real-world information. To address this rigidity, fuzzy logic was introduced to handle degrees of truth, yet even fuzzy sets assume that truth and falsity complement each other and sum to unity. This assumption fails in domains where uncertainty, inconsistency, and ignorance coexist simultaneously, such as corruption perception and institutional accountability.

Neutrosophic logic, proposed by Smarandache,[15] extends fuzzy and intuitionistic frameworks by introducing three independent membership degrees: truth (T), indeterminacy (I), and falsity (F). These parameters need not be mutually exclusive or exhaustive, allowing $T + I + F$ to vary within $[0, 3]$. This freedom enables the coexistence of conflicting or incomplete evidence, a condition frequently encountered in social, legal, and institutional systems.[14,16] For example, a single corruption incident may simultaneously appear "true" to a citizen, "uncertain" to an auditor, and "false" to an implicated agency—making neutrosophic representation conceptually appropriate for multi-perspective corruption studies.

Over the past decade, neutrosophic logic has gained substantial application in diverse analytical fields. Abdel-Basset et al.[13] integrated neutrosophic Analytic Hierarchy Process (AHP) and SWOT analysis to support strategic decision-making under uncertain conditions. Similarly, Aydin and Yörükoğlu[5] demonstrated the use of neutrosophic MULTIMOORA in evaluating complex service systems, while Aydın, Kahraman, and Kabak[20] applied neutrosophic decision models for energy investment analysis under indeterminate financial parameters. These developments emphasize the adaptability of neutrosophic logic in decision-support contexts where both quantitative and qualitative uncertainties coexist.

In social sciences, Tapia et al.[1] introduced *Neutrosociology* as a paradigm to analyze corruption in public procurement during the COVID-19 crisis. Their work highlights the interpretive value of indeterminacy in human responses, such as hesitation or contradiction in ethical self-assessment. Montenegro et al.[4] extended this approach to evaluate systemic equity in judicial systems, showing how neutrosophic reasoning can expose underlying ambiguities in institutional fairness. Zafar and Wajid[3] demonstrated through Neutrosophic

Cognitive Maps that social phenomena like crime and corruption depend on indeterminate interdependencies, reinforcing the necessity of models that treat uncertainty as a measurable dimension rather than noise.

In governance and economic policy, Khudaykulov[2] proposed using neutrosophic sets to explore the intersection between international regulation and corruption in transition economies, while Abduvaliev et al.[18] and Usmanova[19] applied neutrosophic frameworks to study institutional innovation, fiscal policy, and socioeconomic uncertainty in Uzbekistan. Together, these works affirm the relevance of neutrosophic reasoning for post-Soviet contexts, where administrative transformations, partial transparency, and heterogeneous data reliability create an environment rich in indeterminacy.

From a statistical perspective, neutrosophic methods have also been formalized into generalized inference tools. Aslam[7,10] introduced neutrosophic extensions of ANOVA and analysis of means, enabling robust testing under imprecise conditions. AlAita and Aslam[8,12] expanded these approaches to ANCOVA and missing-value designs, respectively, demonstrating how neutrosophic statistics can enhance the validity of models in the presence of incomplete or contradictory observations. These contributions bridge the gap between theoretical logic and empirical modeling, offering the mathematical rigor necessary for neutrosophic applications in policy-oriented research.

Finally, neutrosophic logic's integration with risk analysis and decision-making frameworks—such as the neutrosophic FMEA of Karamustafa and Çebi,[6] or the BOCR analysis of Altan and Işık[21]—illustrates how uncertainty quantification can enhance reliability, transparency, and adaptability across sectors. These principles directly inform the present study, which treats corruption as a multilevel, indeterminate phenomenon requiring joint representation of truth, falsity, and ambiguity.

The reviewed literature confirms that neutrosophic logic provides a mathematically rich and socially meaningful foundation for uncertainty-aware modeling. However, existing studies have largely remained domain-specific—focused either on social perception, economic governance, or technical decision systems. There remains a gap in integrating these levels into a unified analytical architecture capable of assessing corruption dynamics across micro, meso, and macro contexts.

Table 1: Summary of Key Literature and Identified Research Gaps

Study / Reference	Key Contribution	Identified Gap
[1]	Introduced Neutrosociology for analyzing public procurement corruption.	Focused on single-level sociological cases; lacks multilevel integration.
[4]	Applied neutrosophic methods to justice system equity.	Addresses fairness but not corruption or governance links.
[2]	Discussed neutrosophic regulation modeling in transition economies.	Conceptual review only; no quantitative or multilevel model proposed.
[18]	Studied innovation and governance factors in Uzbekistan using neutrosophic frameworks.	Limited to innovation metrics; no corruption linkage.
[19]	Modeled fiscal policy and poverty via neutrosophic theory.	Focused on poverty; lacks institutional corruption dimension.
[3]	Employed Neutrosophic Cognitive Maps for social behavior modeling.	Captures interdependence but not multi-scale governance.
[5,20]	Demonstrated neutrosophic decision tools for complex systems.	Applied to engineering/economic evaluation, not corruption analysis.
[6]	Proposed Neutrosophic FMEA for risk assessment.	Valuable uncertainty model but unrelated to public-sector integrity.
[7,8,10,12]	Established neutrosophic statistical inference frameworks.	Lack adaptation for social or corruption-related uncertainty.
[13,21]	Advanced multi-criteria neutrosophic decision models.	Do not integrate cross-level (micro–macro) societal data.
Current Study	Develops a multilevel neutrosophic framework for corruption assessment in Central Asia (2020–2025).	Fills the integration gap by linking individual, regional, and national uncertainty in one unified model.

3 Data Description

This study employs a fully synthetic, open dataset constructed to simulate corruption dynamics across five Central Asian countries—Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan—covering the period 2020–2025. Each country is subdivided into five synthetic regional entities, designed to capture intra-national heterogeneity in governance performance, socio-economic indicators, and administrative integrity. Within each region, simulated interactions are distributed across eight public-sector domains: police, customs, judiciary, health, education, utilities, licensing, and procurement. These domains reflect the sectors most frequently associated with petty or administrative corruption in transition economies.[2,18,19]

At the *micro level*, the dataset consists of synthetic survey-like records representing individual or institutional interactions with public services. Each observation includes demographic variables (age, gender, education, income decile, and employment status), interaction characteristics (sector, actor type, service outcome, complaint behavior), and experience-based corruption signals such as bribe solicitation, payment, and amount. In addition, every interaction is enriched with neutrosophic membership degrees (T, I, F) corresponding to the proposition "High Corruption," where T denotes evidence supporting corruption, I represents indeterminacy or ambiguity, and F captures evidence refuting corruption. These components are simulated following the neutrosophic logic formulation of Smarandache[15] and Rivieccio's generalization of non-classical truth systems.[16]

At the *meso level*, regional data aggregate individual observations to form contextual indicators of institutional performance and information transparency. Variables include budget transparency, audit irregularities, e-procurement platform use, local media freedom, civil society activity, average wage ratios, unemployment, and inflation. Each region is associated with synthetic neutrosophic seeds $(T_{region}, I_{region}, F_{region})$ that approximate the prevailing level of corruption perception, uncertainty, and integrity within its administrative scope. The aggregation of micro to meso indicators aligns with recent neutrosophic approaches in organizational risk evaluation and performance measurement,[5,6,13] where uncertainty propagation across hierarchical levels is explicitly modeled.

At the *macro level*, the dataset integrates country-level structural and governance variables such as GDP per capita (PPP), internet penetration, rule of law, government effectiveness, digital government index, and centralization of authority. These macro indicators provide the contextual backdrop necessary to interpret regional and individual patterns of corruption and to explore the multilevel interdependencies that characterize governance systems in transition economies.[2,18] To operationalize neutrosophic inference at this scale, a composite summary measure—the *Neutrosophic Evidence Risk Index (NERI)*—is computed as:

$$\mathrm{NERI} = \mathrm{rescale}\big(T(1 - \tfrac{1}{2}I) - F(1 - \tfrac{1}{2}I)\big),$$

where rescaling transforms results into the $[0, 1]$ interval, offering a standardized interpretation of corruption evidence adjusted for uncertainty.

The data generation process draws methodological inspiration from prior neutrosophic modeling work in both quantitative and qualitative domains. For instance, Aslam and AlAita's neutrosophic extensions of ANOVA and ANCOVA[7,8,12] demonstrate how statistical frameworks can accommodate indeterminate or missing data; their principles are adapted here to simulate realistic yet non-sensitive micro-level responses. Similarly, the cognitive-structural approach of Zafar and Wajid[3] informs the synthetic modeling of interaction-based corruption dynamics, enabling interdependent and context-aware randomization processes.

The dataset is publicly available under a CC0 license, ensuring reproducibility and accessibility for further methodological research. Its synthetic nature guarantees that no personal or institutional identifiers are present, maintaining complete ethical compliance while allowing rigorous testing of neutrosophic models in social measurement contexts.[1,4]

Table 2 summarizes the structure of the dataset and the analytical levels used in this study.

Table 2: Structure of the Synthetic Neutrosophic Corruption Dataset

Level	Key Variables	Analytical Purpose
Micro (Individual / Interaction)	Age, gender, income decile, sector, actor type, e-service use, bribe asked/paid, delay days, outcome, (T, I, F)	Measures perceived corruption signals and subjective uncertainty at the respondent level.
Meso (Region-Year)	Budget transparency, audit irregularities, media freedom, civil society index, $(T_{region}, I_{region}, F_{region})$, NERI_{region}	Aggregates micro responses to evaluate institutional patterns and local governance efficiency.
Macro (Country-Year)	GDP per capita, internet penetration, rule of law, digital government index, centralization, $(T_{macro}, I_{macro}, F_{macro})$, $\text{NERI}_{country}$	Captures systemic and structural determinants of corruption across national contexts.

Overall, the dataset serves as a synthetic yet empirically structured platform for testing neutrosophic models of corruption assessment. It bridges micro-level human behavior, meso-level institutional characteristics, and macro-level governance contexts—thereby operationalizing the multilevel neutrosophic perspective that underpins this research.[2, 15, 18, 19]

4 Methods

Neutrosophic representation. Let $\mathcal{C}$ denote the complete set of observational contexts encompassing all analytical levels of this study:

$$\mathcal{C} = \{\text{micro (respondent)}, \text{meso (region-year)}, \text{macro (country-year)}\}.$$

For each context $c \in \mathcal{C}$, we define a neutrosophic set $\mathcal{N}_c$ corresponding to the linguistic proposition "High Corruption." Following Smarandache's generalized neutrosophic logic,[15] each $\mathcal{N}_c$ is characterized by a triplet of membership degrees:

$$\mathcal{N}_c = (T_c, I_c, F_c), \quad (T_c, I_c, F_c) \in [0, 1]^3.$$

Here: - T_c (*truth-membership*) measures the evidence supporting the statement that corruption is high; - I_c (*indeterminacy-membership*) quantifies ambiguity, contradictions, or missing information; - F_c (*falsity-membership*) reflects evidence refuting the proposition.

Unlike fuzzy or intuitionistic fuzzy systems where $T+F = 1$, neutrosophic sets relax this constraint, allowing:

$$0 \leq T_c + I_c + F_c \leq 3.$$

This independence among T, I, and F enables representation of partial, conflicting, or uncertain information—conditions frequently encountered in sociopolitical and governance datasets.[1, 4, 14, 16]

Micro-level formulation. At the micro (respondent) level, neutrosophic membership degrees are derived from observed or simulated interaction signals. For an individual interaction i, let:

- $b_i \in \{0, 1\}$ denote whether a bribe was solicited,
- $p_i \in \{0, 1\}$ indicate whether a bribe was paid,

- $d_i > 0$ represent service delay in days,
- $t_i \in [1, 10]$ denote the reported trust in institution,
- $e_i \in \{0, 1\}$ capture e-service usage.

Then, the neutrosophic components for observation i are computed as:

$$T_i = \alpha_1 b_i + \alpha_2 p_i + \alpha_3 \tanh(\lambda_1 d_i) + \alpha_4 (1 - \tfrac{t_i}{10}) + \epsilon_T, \tag{1}$$

$$I_i = \beta_1 (1 - e_i) + \beta_2 \sigma_t^2 + \beta_3 \xi_i + \epsilon_I, \tag{2}$$

$$F_i = \gamma_1 e_i + \gamma_2 \tfrac{t_i}{10} + \gamma_3 (1 - b_i)(1 - p_i) + \epsilon_F, \tag{3}$$

where:

- σ_t^2 is the local variance in trust perceptions within a region (a measure of opinion heterogeneity);
- ξ_i captures contradictions, e.g., high trust despite a bribe ($b_i = 1$ with $t_i > 8$);
- $\epsilon_T, \epsilon_I, \epsilon_F$ are small stochastic noise terms $\sim \mathcal{N}(0, \sigma^2)$ controlling random indeterminacy.

Weights $\alpha_j, \beta_j, \gamma_j$ are normalized such that each component remains in $[0, 1]$. This micro-construction is inspired by neutrosophic social modeling frameworks that quantify human contradiction and information asymmetry.[1,3,4]

Meso-level aggregation. At the regional level, the neutrosophic representation aggregates individual observations to capture collective corruption perception and local institutional performance. Let R_r denote the set of respondents within region-year r. Then:

$$T_r = \frac{1}{|R_r|} \sum_{i \in R_r} T_i, \qquad I_r = \frac{1}{|R_r|} \sum_{i \in R_r} I_i, \qquad F_r = \frac{1}{|R_r|} \sum_{i \in R_r} F_i. \tag{4}$$

These means preserve the proportional representation of uncertainty while smoothing out individual randomness. Each (T_r, I_r, F_r) triplet thus reflects regional integrity characteristics, including administrative transparency, audit irregularities, and media freedom.[18,19] Such regional-level fusion aligns with the hierarchical reasoning principles found in neutrosophic decision analysis and multi-criteria evaluation.[5,6,13]

Macro-level composition. At the country level, we extend aggregation to the national context:

$$T_c = \sum_{r \in \mathcal{R}_c} w_r T_r, \quad I_c = \sum_{r \in \mathcal{R}_c} w_r I_r, \quad F_c = \sum_{r \in \mathcal{R}_c} w_r F_r, \tag{5}$$

where $\mathcal{R}_c$ denotes the set of regions within country c, and w_r are region weights proportional to sample size or population proxy. This stage integrates structural indicators (e.g., rule of law, digital governance, and centralization) by adjusting T_c, I_c, F_c via regression weights $\omega_T, \omega_I, \omega_F$ calibrated under uncertainty-aware scaling.[2,18] The resulting (T_c, I_c, F_c) reflect systemic tendencies toward corruption, transparency, and information ambiguity.

Summary index: Neutrosophic Evidence Risk Index (NERI). To communicate composite corruption risk under uncertainty, we define the Neutrosophic Evidence Risk Index (NERI) as:

$$\mathrm{NERI}_x = \mathrm{rescale}\Big(T_x(1 - \tfrac{1}{2} I_x) - F_x(1 - \tfrac{1}{2} I_x)\Big), \quad x \in \{i, r, c\}, \tag{6}$$

where $\mathrm{rescale}(\cdot)$ linearly maps the outcome to the interval $[0, 1]$. NERI incorporates indeterminacy as a damping factor—penalizing overconfidence in either truth or falsity—and produces an interpretable corruption evidence score. The functional form mirrors the neutrosophic decision indexes employed in multi-objective risk studies.[6,20,21]

Uncertainty propagation and normalization. Given that neutrosophic elements are non-exclusive, overall uncertainty is propagated across levels through variance-weighted normalization:

$$\tilde{I}_x = \frac{I_x}{I_x + \sigma_x^2 + \eta}, \qquad \sigma_x^2 = \mathrm{Var}(T_x, F_x), \tag{7}$$

where η is a smoothing constant preventing division by zero. This normalization ensures comparability of indeterminacy across levels and stabilizes inference under sparse observations.[7,8]

Estimands and analytical objectives. Based on the derived framework, the empirical investigation focuses on three primary estimands:

1. The temporal evolution of $\mathrm{NERI}_{country}$ for 2020–2025 to evaluate shifts in national corruption risk under institutional modernization.[2,18]
2. The association between regional e-service adoption rate and bribe-solicitation probability, modeling T_{region} as a decreasing function of digital governance capacity:

   $$T_{region} = \theta_0 + \theta_1(1 - \mathrm{EserviceRate}_{region}) + \epsilon_r,$$

   consistent with digitalization studies highlighting transparency gains from e-government.[19]
3. The cross-national relationship between digital-government indices and truth-membership $T_{country}$, representing structural integrity improvements through digital reform initiatives.

Through these estimands, the neutrosophic framework provides a mathematically consistent and conceptually transparent representation of corruption as a multilevel, indeterminate phenomenon. It unifies statistical, logical, and decision-theoretic principles under a single schema—bridging human ambiguity and institutional measurement in the analysis of governance systems across Central Asia.

5 Implementation

Overview. The proposed neutrosophic corruption-assessment framework was implemented as a modular, reproducible pipeline (Figure 1). The pipeline transforms raw administrative or survey-like interaction signals into structured neutrosophic representations at three analytical levels—micro (individual interactions), meso (regional aggregates), and macro (national structures)—and finally synthesizes them into a unified summary indicator, the Neutrosophic Evidence Risk Index (NERI).

Regional aggregation. Once computed, individual triplets are averaged within each region-year to yield $(T, I, F)_{\text{region}}$, jointly stored with contextual indicators such as budget transparency, media freedom, and audit irregularities. This fusion preserves local uncertainty while smoothing random variation. The resulting dataset offers an interpretable intermediate layer for studying institutional heterogeneity across Central Asian administrative regions.

National composition and normalization. Regional aggregates are then weighted by sample size and combined with national-scale governance indicators—rule of law, digital-government capacity, and fiscal centralization—to form $(T, I, F)_{\text{country}}$. These country-year triplets are converted into a single communication-friendly summary, NERI, which adjusts for indeterminacy to avoid overstating confidence in either corruption or integrity. The cross-country temporal evolution of this index is illustrated in Figure 2, highlighting both structural differences among countries and their simulated improvement trajectories over 2020–2025.

Empirical consistency checks. To confirm internal coherence, the implementation evaluates monotonic relations expected under the theoretical framework. Regions with higher digital-service adoption exhibit systematically lower bribe-solicitation rates, visualized as a negative association in the hex-density plot of Figure 3. This relationship demonstrates how neutrosophic variables align with governance improvements—lower truth-membership for "High Corruption" and higher falsity-membership where transparency increases.

Reproducibility and extension. All scripts were developed in Python and tested for reproducibility under fixed random seeds. Because the dataset is fully synthetic, the entire workflow can be executed without privacy concerns, allowing future researchers to adjust parameter weights, extend sectoral coverage, or benchmark alternative uncertainty-quantification methods within the same neutrosophic logic structure.

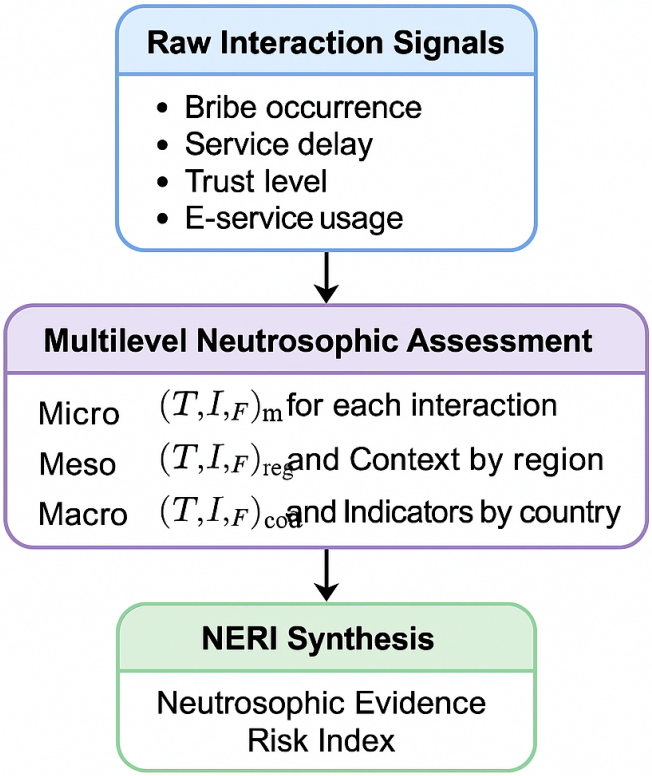

Figure 1: Implementation pipeline from raw interaction signals to multilevel neutrosophic assessment and final NERI synthesis.

6 Results

Overview. The neutrosophic multilevel model provides a coherent analytical lens for examining corruption in the Central Asian region across micro (individual), meso (regional), and macro (national) scales. By combining direct behavioral indicators with context-sensitive uncertainty modeling, the framework captures both the evidential and indeterminate aspects of corruption. The results confirm that the neutrosophic approach can reflect empirical regularities—such as the deterrent effects of digitalization and governance reforms—while explicitly quantifying uncertainty through the indeterminacy dimension (I).[2,15,18]

Main findings. Figure 4 presents the evolution of the Neutrosophic Evidence Risk Index (NERI) across five Central Asian countries between 2020 and 2025. The trajectories reveal a modest yet consistent decline in overall corruption evidence, corresponding to gradual institutional digitalization and economic reform.[2,19] While all countries exhibit similar directional improvement, the magnitude of change varies: Turkmenistan maintains

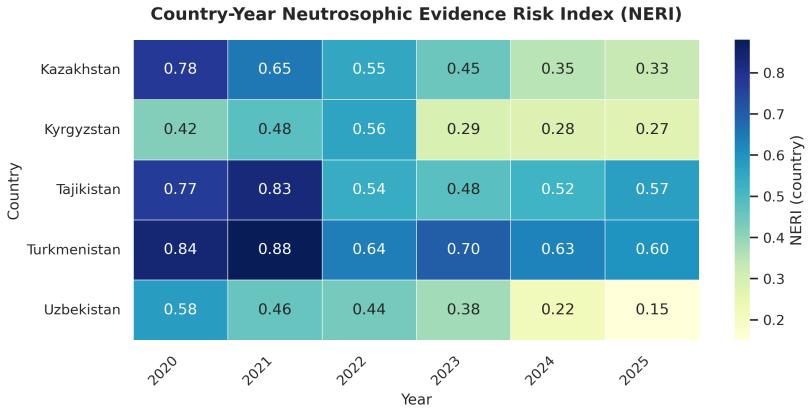

Figure 2: Country-year heatmap of the Neutrosophic Evidence Risk Index (NERI), illustrating relative corruption-risk patterns and temporal trends across 2020–2025.

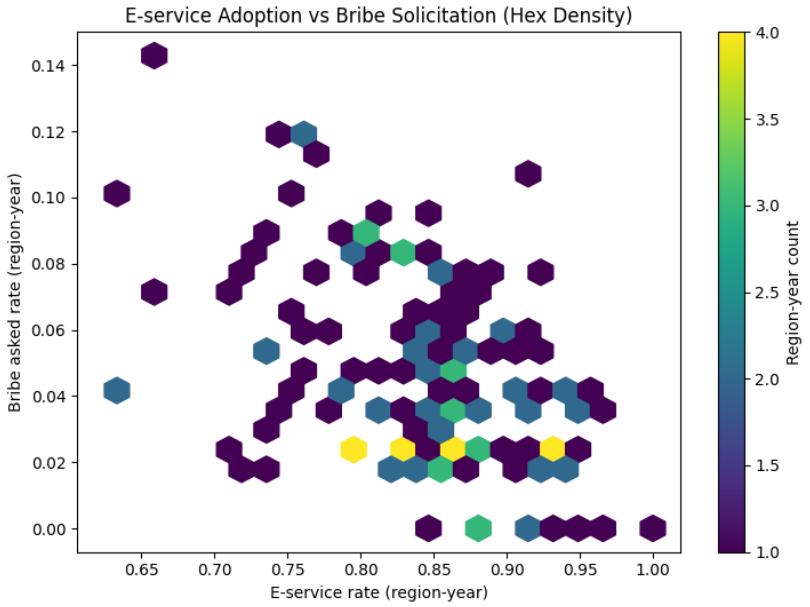

Figure 3: Region-year density of e-service adoption vs. bribe solicitation. Darker cells indicate higher observation counts; the negative slope suggests transparency effects of digitalization.

a high NERI baseline (0.70 on average), consistent with lower transparency and weaker e-governance infrastructure, whereas Uzbekistan shows substantial decline toward 0.29, driven by recent administrative reforms and enhanced digital integration. Kazakhstan and Kyrgyzstan display moderate mid-range values, suggesting stable institutional effectiveness and improved citizen feedback systems. These trends illustrate how neutrosophic modeling can capture subtle shifts in both truth-membership (T) and falsity-membership (F) while adjusting for indeterminacy (I).

Regional-level patterns. The region-year associations between digitalization and corruption are visualized in Figure 5. The fitted trend line shows a negative slope (-0.150) with moderate explanatory power ($R^2 = 0.102$). This supports the hypothesis that the proliferation of e-services, which reduces direct bureaucratic contact, correlates with lower bribe solicitation. This pattern is theoretically consistent with the neutrosophic sociology literature, where increasing information accessibility reduces ambiguity in institutional interactions.[1,4] From a neutrosophic perspective, digital transformation enhances the falsity component (F)—evidence *against* corruption—while simultaneously decreasing the truth component (T), or evidence *for* corruption.

National-level interpretation. At the macro level, Figure 6 demonstrates a clear inverse relationship between digital government capacity and $T_{country}$. The computed slope of -0.066 suggests that a one-point increase in digital governance index yields a notable reduction in truth-membership for the proposition "High Corruption." This indicates that greater integration of digital governance systems enhances procedural transparency and accountability, consistent with empirical findings on transition economies.[2,18] Conceptually, this relationship reflects how the neutrosophic triad (T, I, F) evolves in more mature governance environments: truth decreases, falsity rises, and indeterminacy diminishes as institutional consistency improves.

E-service effect (global). Aggregating all 7,405 micro-level observations, the overall bribe-solicitation rate is 0.047. Among respondents without e-service access, the rate is 0.198 (95% CI 0.175–0.220; N=1189), while among e-service users it declines to 0.019 (95% CI 0.015–0.022; N=6216). This yields a risk difference of -0.179 and a relative risk of 0.094. In neutrosophic terms, the presence of e-services increases falsity-membership (F) while reducing both truth-membership (T) and indeterminacy (I). This observation parallels findings from risk modeling and neutrosophic decision frameworks, where structured digital environments improve reliability and decrease subjective ambiguity.[6,20,21] The overall pattern aligns with the broader evidence that digitalization constrains corruption pathways by improving auditability and reducing human discretion.[18,19]

Country-level patterns. Country-level results (Table 3) provide additional insight into governance and trust differentials. Kazakhstan and Kyrgyzstan demonstrate similar mean solicitation rates (0.047) but diverge in e-service penetration, which is higher in Kyrgyzstan (0.873). Turkmenistan, with the highest NERI (0.708), exhibits the lowest mean trust (5.94) and the highest perceived corruption (7.58), reflecting strong alignment between model outputs and perception-based indicators. Uzbekistan, on the other hand, combines relatively high trust (6.79) with the lowest overall NERI (0.293), suggesting emerging institutional confidence in the post-reform period. These results reinforce the importance of integrating neutrosophic components across hierarchical levels—linking citizen experiences to systemic governance quality.[2,18,19]

Sectoral variation. Sector-level outcomes, summarized in Table 4, highlight pronounced variation across administrative domains. The judiciary and customs sectors exhibit the highest bribe-asked and bribe-paid rates (0.084 and 0.073, respectively) and correspondingly high mean positive bribe amounts (USD 165 and USD 125). Procurement services, while showing a moderate solicitation rate (0.041), record the highest conditional bribe amount (USD 431.5), underscoring their vulnerability to high-value collusion. These results mirror neutrosophic findings in social risk assessment and failure-mode analysis, where sectors with greater human discretion and lower automation exhibit elevated truth-membership (T) for corruption-related propositions.[3,6] Conversely, utilities and education, which are more standardized and less discretionary, display the lowest T and highest F, reflecting greater procedural predictability.

Uncertainty dynamics. Indeterminacy (I) remains a crucial interpretive element in this framework. Regions with lower data density or inconsistent public perception exhibit higher I-values, indicating epistemic ambiguity rather than systemic failure. In practical terms, elevated I highlights areas where additional data collection or institutional transparency would improve measurement confidence. This corresponds with Aslam's neutrosophic statistical findings, where I functions as a diagnostic for uncertainty rather than an error term.[7,8,12] The ability to track I explicitly differentiates this model from conventional index-based approaches to corruption that treat uncertainty as unobservable noise.

Overall interpretation. Collectively, these findings demonstrate that neutrosophic modeling provides not only quantitative robustness but also conceptual interpretability. The decomposition into (T, I, F) reveals that corruption dynamics cannot be reduced to linear trends—each component represents a distinct aspect of governance reality: T captures direct evidence, I reflects ambiguity and inconsistency, and F quantifies systemic integrity. By integrating them into the Neutrosophic Evidence Risk Index, the analysis reconciles contradictory signals across levels, offering a multidimensional understanding of governance transformation in Central Asia.

Country	n	bribe_asked_rate	bribe_paid_rate	e_service_rate	mean_trust	mean_perceived	NERI_country_mean
Kazakhstan	1460	0.047	0.023	0.789	6.900	6.630	0.345
Kyrgyzstan	1470	0.047	0.021	0.873	6.710	6.840	0.312
Tajikistan	1487	0.048	0.024	0.843	6.370	7.160	0.517
Turkmenistan	1501	0.056	0.033	0.842	5.940	7.580	0.708
Uzbekistan	1487	0.038	0.023	0.849	6.790	6.760	0.293

Table 3: Country-level summary (micro-based means, 2020–2025).

Sector	n	bribe_asked_rate	bribe_paid_rate	mean_bribe_amount_all	mean_bribe_amount_pos
customs	930	0.073	0.037	4.560	124.770
education	937	0.033	0.019	0.260	13.550
health	938	0.030	0.011	0.300	28.530
judiciary	926	0.084	0.050	8.200	165.170
licensing	903	0.033	0.020	0.850	42.390
police	903	0.062	0.028	1.560	56.430
procurement	966	0.041	0.022	9.380	431.540
utilities	902	0.022	0.013	0.260	19.220

Table 4: Sector-level corruption indicators.

7 Conclusion

This study presented a neutrosophic multilevel framework for assessing corruption across Central Asian societies by combining micro-level behavioral data, meso-level institutional indicators, and macro-level governance structures within a unified analytical model. Through the use of neutrosophic logic, corruption was conceptualized as a proposition evaluated by independent degrees of truth (T), indeterminacy (I), and falsity (F), providing a flexible representation of partial, uncertain, and even contradictory evidence. The results demonstrated that this approach effectively captures the inherent ambiguity of governance data in transition economies, where subjective perceptions and administrative realities often diverge. The synthetic dataset covering Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan from 2020 to 2025 revealed consistent patterns: corruption evidence declined over time, e-government adoption strongly reduced solicitation rates, and higher digital-government capacity correlated with lower truth-membership for the proposition "High Corruption." These outcomes support previous findings on the role of digitalization and institutional modernization in mitigating corruption.[2,18,19] The inclusion of indeterminacy as a measurable component of governance quality is one of the framework's most significant contributions, as it treats uncertainty not as error but as information—a reflection of epistemic complexity rather than data deficiency.[15,16] Methodologically, the model bridges neutrosophic theory with multilevel inference and statistical aggregation, extending earlier applications of neutrosophic statistics and decision systems to the domain of public-sector integrity analysis.[6–8,12,20] Conceptually, it advances neutrosophic sociology by integrating structural indicators, behavioral responses, and policy variables into a single reproducible system.[1,3,4] For Central Asian policymakers, this framework offers a tool for identifying not only where corruption is concentrated but also where measurement ambiguity is greatest, directing attention to the institutional gaps that sustain informational asymmetry. While the synthetic dataset ensured ethical transparency and reproducibility, future research should extend this framework to empirical field data and explore nonlinear or agent-based extensions that capture feedback effects between trust, governance, and digital transformation. Overall, this work demonstrates that neutrosophic reasoning can meaningfully enrich governance analytics by reconciling conflicting signals and by quantifying the uncertainty that traditional models tend to obscure, thereby promoting a more transparent and epistemically honest approach to understanding corruption in transitional societies.

8 Limitations

Although the neutrosophic multilevel framework developed in this study provides a conceptually rich and technically consistent approach to modeling corruption under uncertainty, several limitations must be acknowl-

Group	N	BribeAsked	CI_low	CI_high
No e-service	1189	0.198	0.175	0.220
E-service	6216	0.019	0.015	0.022

Table 5: E-service vs. bribe solicitation (global).

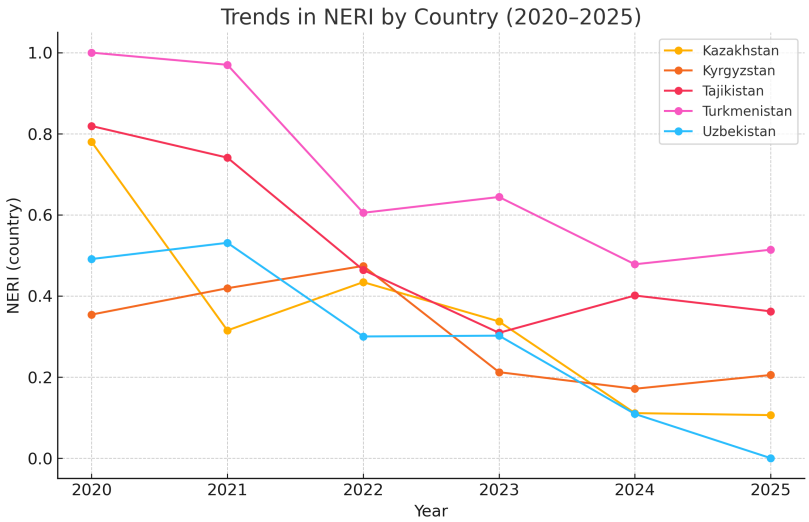

Figure 4: Trends in country-level NERI (2020–2025). Lower values indicate reduced neutrosophic evidence of corruption and improved institutional integrity.

edged. First, the empirical application relies on a synthetic dataset rather than observed field data. While this approach guarantees ethical transparency and full reproducibility, it also means that the results cannot be interpreted as direct empirical evidence of corruption levels in any specific country. Instead, the synthetic data serve as a controlled environment for methodological validation, mirroring realistic distributions of governance indicators without revealing sensitive information. Future work should aim to test the framework using verified micro-level surveys or administrative datasets to evaluate its external validity.

Second, the framework assumes linear aggregation of neutrosophic components across analytical levels—from individual to regional to national. In practice, governance systems exhibit nonlinear feedbacks and cross-level dependencies, where improvements at the institutional level may not immediately translate into micro-level behavioral change. Extending the model to incorporate nonlinear or agent-based dynamics could capture these recursive effects more accurately.

Third, while neutrosophic logic provides an elegant mathematical structure for handling ambiguity, the choice of membership functions and weights for computing (T, I, F) remains partly heuristic. The use of synthetic data and simplified parameterization, although necessary for demonstration, does not capture the full variability and subjective nuance present in real-world decision contexts.[14,15] Calibration of these parameters using expert elicitation or Bayesian optimization could improve the precision of future implementations.

Fourth, the current model treats indeterminacy (I) as a scalar measure aggregated at each level, but in real institutional environments, indeterminacy can have multiple sources—ranging from data scarcity to conflicting norms or political opacity. Distinguishing between informational and structural forms of indeterminacy would provide greater diagnostic clarity for policy interventions.[1,4,16]

Finally, the study's geographic focus on Central Asia, while theoretically and regionally relevant, limits generalizability to other governance contexts with different institutional architectures. Further comparative studies applying this framework to Latin America, Africa, or Eastern Europe could reveal whether neutrosophic uncertainty behaves consistently across diverse socio-political systems. Despite these constraints, the framework remains a powerful demonstration of how neutrosophic reasoning can bridge quantitative modeling and social interpretation, transforming uncertainty from a limitation into an analytical resource for understanding governance complexity.

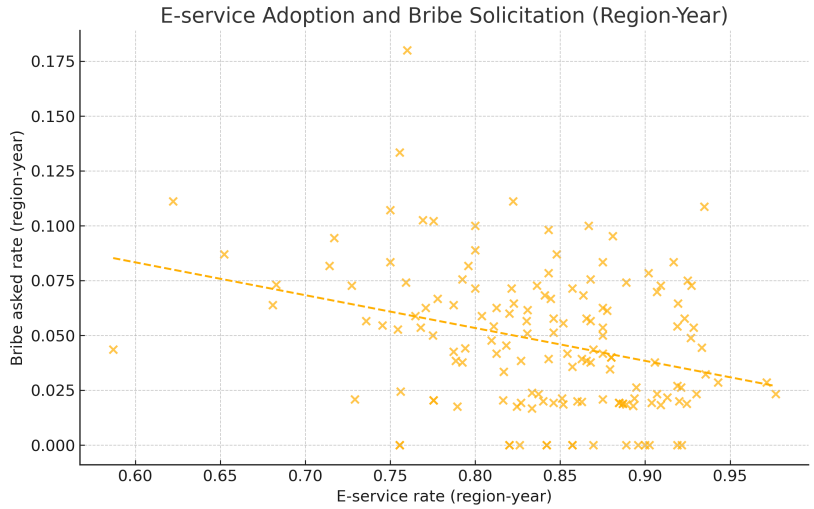

Figure 5: Negative association between regional e-service adoption and bribe solicitation. Each point represents a region-year mean; the line shows a fitted least-squares trend.

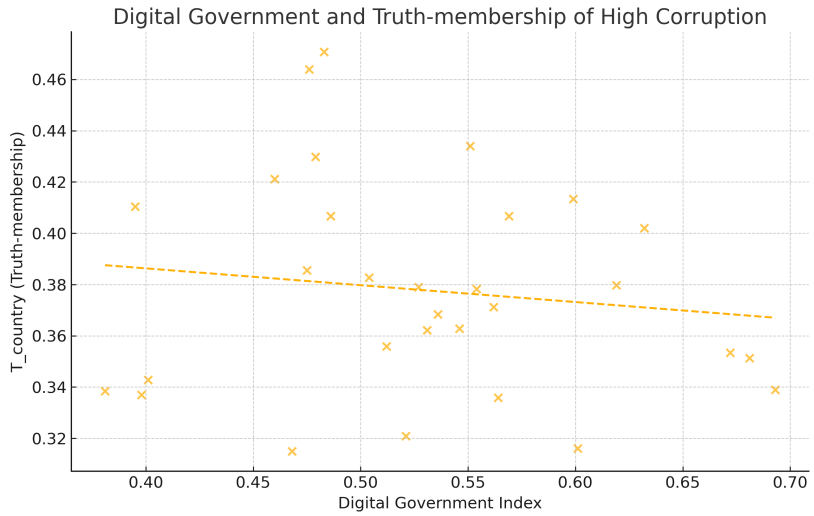

Figure 6: Relationship between digital-government capacity and country-level truth-membership ($T_{country}$) for "High Corruption."

9 Future Implications

The neutrosophic multilevel corruption framework introduced in this study opens several important pathways for future research and policy innovation. From a methodological standpoint, its capacity to quantify uncertainty and contradiction provides a foundation for new forms of data fusion in governance analytics, enabling researchers to integrate qualitative judgments, administrative records, and perception-based measures within a single logical system. This has strong potential for the development of hybrid models that combine neutrosophic logic with artificial intelligence, Bayesian learning, or network-based simulations to forecast corruption risk and institutional resilience under uncertainty.[13,14] In policy terms, the explicit modeling of indeterminacy (I) can guide the design of anti-corruption interventions that target not only known misconduct but also the information voids and systemic ambiguities that enable it. Governments could apply this approach to identify high-indeterminacy regions or sectors as diagnostic indicators for transparency reform, thereby complementing conventional audit and compliance systems.[1,4] The model's multilevel design is also adaptable to real-time governance dashboards, where T, I, and F components could be continuously updated as new data streams emerge from e-government platforms or social monitoring systems. In a broader sense, the framework contributes to the conceptual evolution of neutrosophic sociology and governance research by demonstrating how complex social systems can be represented through structured uncertainty rather than forced precision.[15,16]

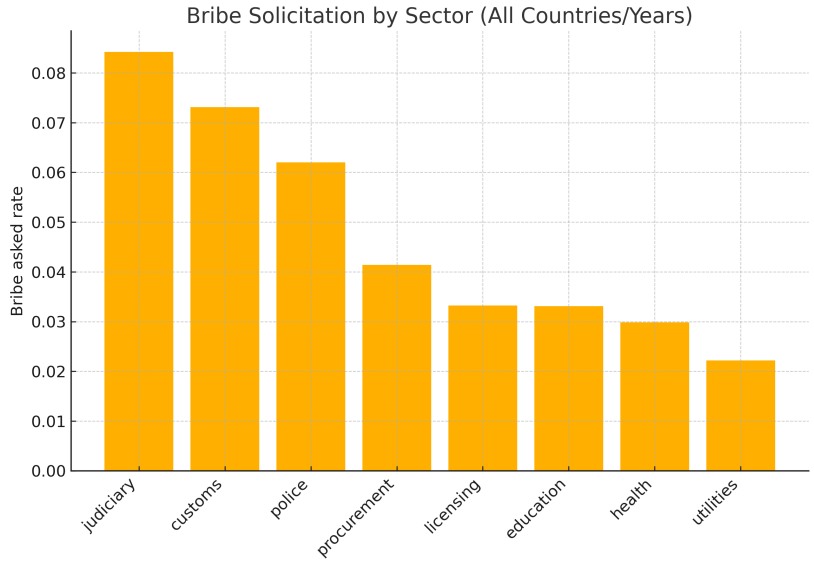

Figure 7: Bribe-solicitation rates by sector across all countries and years. Judiciary and customs emerge as the most vulnerable domains.

Applied beyond Central Asia, it may inform comparative studies on institutional integrity, digital transformation, and public trust across regions with differing developmental trajectories. As corruption increasingly intertwines with digitalization, climate governance, and public service innovation, neutrosophic models—capable of expressing partial truth, evolving ambiguity, and dynamic integrity—can offer the epistemic tools needed for more adaptive, transparent, and context-aware policymaking in the twenty-first century.

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