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Beyond Deterministic Models: Neutrosophic Insights into Cognitive Depth Assessment in Ghanaian Tertiary Institutions

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Abstract
This study explored the application of neutrosophic analysis to assess Depth of Knowledge (DoK) levels among mathematics students in a Ghanaian tertiary institution. Data from 51 students from Ada College of Education, Ghana were analyzed, incorporating test scores across Trigonometry, Functions, Algebra, Probability, and Calculus domains as predictors. Neutrosophic ternary plots, heatmaps, and boxplots revealed significant indeterminacy in advanced cognitive classifications, underscoring limitations in deterministic assessment models. Moderation and mediation analyses confirmed M1's significant role in influencing predictor-outcome dynamics. The findings advocate for integrating uncertainty measures in educational assessments to enhance cognitive classification reliability and instructional responsiveness.
Keywords. *Assessment uncertainty, Cognitive classification, Depth of Knowledge, Educational diagnostics, Foundational mathematics.*

INTRODUCTION AND LITERATURE REVIEW

Cognitive assessments in higher education often rely on deterministic classification frameworks that may overlook inherent uncertainties, particularly in complex domains such as mathematics [1-9]. Depth of Knowledge (DoK) frameworks, though widely adopted, typically assign students categorically without accommodating ambiguity in cognitive profiles. Recent research emphasizes the need for probabilistic or uncertainty-aware approaches to capture nuanced student competencies Neutrosophic logic, introduced by Smarandache [7], provides a flexible framework capable of quantifying truth, indeterminacy, and falsity degrees simultaneously, offering potential to address these assessment limitations [6, 33-41].

In Ghanaian tertiary institutions, mathematics assessments remain rigidly deterministic [10-32], with minimal consideration of classification uncertainty. Studies [10-32] have highlighted significant variability in cognitive outcomes among advanced mathematics students, suggesting the need for alternative assessment models that recognize indeterminate classifications. This study builds on existing literature by integrating neutrosophic analysis with multinomial logistic regression to assess DoK classifications in mathematics education. It further explores the role of foundational mathematics in shaping cognitive classification outcomes through mediation and moderation frameworks.

METHODS

A cross-sectional design was adopted, utilizing mathematics test data from 51 students enrolled in a Ghanaian tertiary institution (Ada College of Education). The dependent variable was the Depth of Knowledge (DoK) level, categorized from Level 1 to Level 4. Independent variables included domain-specific mathematics scores: TMAT, MFUNC, MALG, MPROB, and MCAL. A census sampling approach was employed due to the small population size and the need to maximize statistical power. Neutrosophic analysis quantified the degrees of truth, indeterminacy, and falsity in DoK classifications, operationalizing Smarandache's framework within the educational assessment context. Data visualizations included ternary plots, heatmaps, stacked bar charts, boxplots, and scatterplots to elucidate neutrosophic components and classification reliability.

RESULTS

Neutrosophic ternary plots revealed that students classified under DoK Levels 1 and 2 predominantly clustered within high truth and low indeterminacy zones. In contrast, DoK Level 4 classifications displayed greater indeterminacy and occasional falsity, indicating uncertainty in advanced classifications. The heatmap of neutrosophic degrees showed that while most students had high truth components (above 0.75), indeterminacy levels varied considerably, particularly among Level 4 students. Falsity degrees remained minimal but were present in isolated cases. Stacked bar charts and boxplots confirmed that truth dominated classification outcomes, with a median above 0.80, while indeterminacy exhibited substantial variability (median = 0.35). Falsity components were minimal overall but spiked for certain students, suggesting misclassification.

Figure 1 presents a **neutrosophic ternary plot** illustrating the distribution of students' Depth of Knowledge (DoK) levels based on their degrees of **truth**, **indeterminacy**, and **falsity**. Each data point represents a student, with points colored according to their assigned DoK level (Levels 1 to 4). The distribution reveals that most students cluster near the axis representing a **high degree of truth and low degree of falsity**, indicating consistent and certain classification into their respective DoK levels. Notably, data points associated with **DoK Levels 1 and 2** are concentrated near the lower indeterminacy region, implying that their cognitive classification is supported by strong evidence and minimal uncertainty. In contrast, students classified as **DoK Level 4** exhibit greater dispersion, with higher degrees of **indeterminacy** and occasional proximity toward the **degree of falsity** axis. This pattern suggests that the classification of advanced cognitive depth (DoK Level 4) is subject to increased uncertainty, potentially reflecting inconsistencies in underlying competencies or the limits of deterministic assessment models.Foundational and intermediate cognitive classifications (DoK Levels 1 and 2) are more certain and reliable, whereas classifications at higher cognitive levels (particularly DoK Level 4) carry increased indeterminacy, highlighting greater classification uncertainty or cognitive variability among advanced students.The findings suggest that current assessment frameworks are robust in classifying lower and intermediate DoK levels but may inadequately capture the complexity associated with advanced cognitive development. Educational assessments may benefit from incorporating uncertainty measures explicitly, allowing educators to identify and support students whose cognitive classifications are probabilistic rather than deterministic.To this end, the neutrosophic analysis provides a nuanced understanding of classification reliability across DoK levels, emphasizing the need to address indeterminacy in advanced cognitive assessment through both instructional and evaluative innovations.

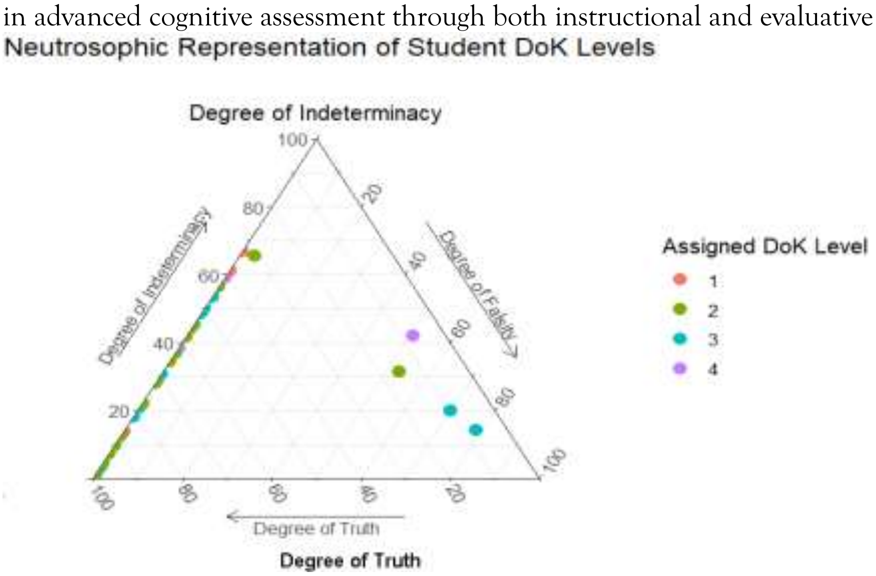

Figure 1: *Neutrosophic Ternary Plot of Students' Depth of Knowledge Classifications Based on Degrees of Truth, Indeterminacy, and Falsity*

Figure 2 presents a **heatmap of neutrosophic degrees by student**, illustrating the distribution of **truth, indeterminacy, and falsity** components across all assessed students. Each row represents a student's assessment classification, with color intensity indicating the magnitude of each neutrosophic degree (from 0 to 1).The **Degree of Truth** component dominates the dataset, as reflected by the dense and consistently darker shading in the first column. This indicates that for the majority of students, classifications into their respective Depth of Knowledge (DoK) levels were based on strong certainty, with truth degrees frequently approaching or exceeding 0.75 across cases. The **Degree of Indeterminacy** exhibits greater variability, with a spectrum ranging from low to moderately high values. This variability signals the presence of uncertainty in classifying several students, particularly those whose competencies may not align neatly with established cognitive categories. Some students display high degrees of indeterminacy, suggesting ambiguous placement within the DoK framework. The **Degree of Falsity** remains minimal for most students, as evidenced by the sparse and faint shading in the falsity column. However, isolated instances of higher falsity degrees are present, indicating misclassification risks or performance profiles that directly contradict expected DoK classifications for a few students. Most students were classified with high certainty (truth), but indeterminacy levels reveal latent classification uncertainties, especially among cognitively ambiguous cases. Low falsity suggests that outright misclassifications are rare but do occur sporadically. The heatmap highlights the utility of neutrosophic analysis in capturing nuanced classification confidence at the individual student level. Instructionally, students displaying higher indeterminacy should be targeted for diagnostic support and personalized interventions to resolve classification ambiguities. Moreover, sporadic falsity peaks warrant further investigation to identify and address potential assessment or instructional mismatches contributing to misclassification. Overall, this visualization emphasizes the importance of incorporating uncertainty-aware frameworks in educational assessment and decision-making, ensuring that intervention strategies account for both certainty and indeterminacy in cognitive classifications.

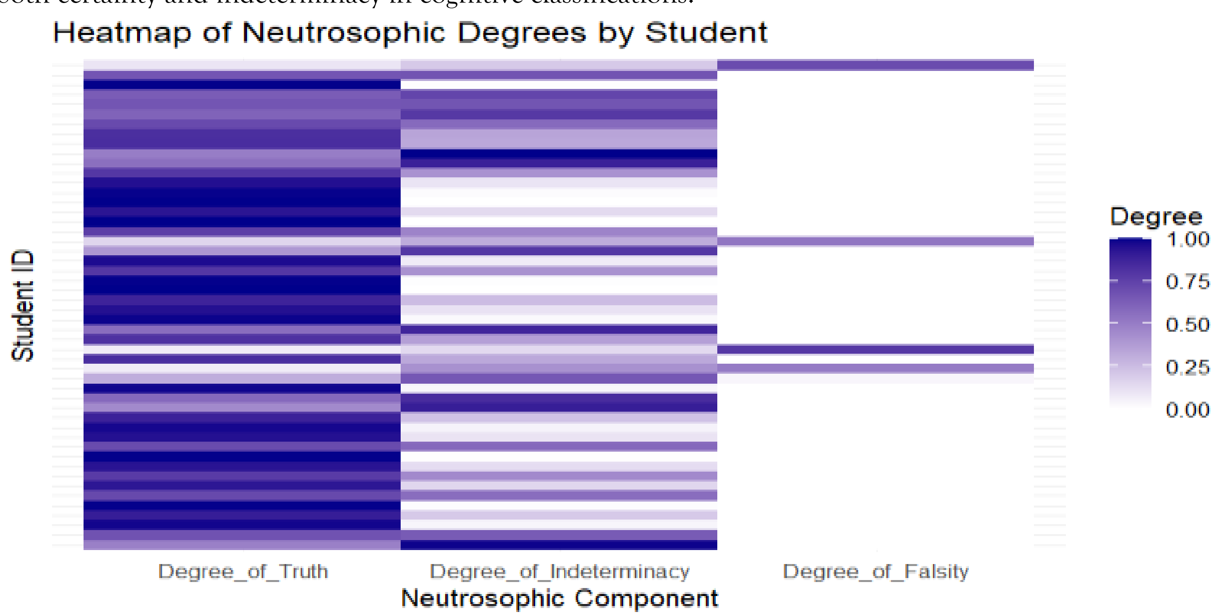

Figure 2: *Heatmap of Neutrosophic Components (Truth, Indeterminacy, Falsity) Across Individual Student Classifications*

Figure 3 illustrates the distribution of **neutrosophic degrees per student**, capturing the relative contributions of **truth**, **indeterminacy**, and **falsity** components for each assessed student. The stacked bar chart clearly shows that the **Degree of Truth** (red bars) dominates across most students, consistently representing the largest component of classification certainty. In some cases, truth values exceed a cumulative degree of 2.0, indicating exceptionally strong certainty in classification for select students. The **Degree of Indeterminacy** (green bars) varies considerably between students, ranging from near-zero to approximately 0.9. This indicates that while many students exhibit confident classifications, others are subject to substantial uncertainty. Notably, the presence of significant indeterminacy among some students suggests cognitive ambiguity,

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potentially due to borderline competencies or limitations in the current assessment framework to fully capture their learning profiles. The **Degree of Falsity** (blue bars) remains minimal for the majority of students but is visibly present for certain cases. This indicates occasional inconsistencies between students' observed performance and their assigned Depth of Knowledge (DoK) levels, highlighting cases of possible misclassification or atypical learning pathways. Most students were assessed with high certainty (truth degree), but non-negligible levels of indeterminacy and occasional falsity degrees were observed across the sample, revealing classification uncertainties and sporadic misclassifications. Students with high indeterminacy or non-trivial falsity degrees represent cognitively vulnerable or atypical profiles that require targeted instructional attention. The variability in indeterminacy further emphasizes that assessment reliability is not uniform across all students. Educational interventions should prioritize reducing classification uncertainty, particularly for students with high indeterminacy. Additional diagnostic assessments may be necessary to clarify cognitive standing for students with elevated falsity components. The model's capacity to visualize and quantify uncertainty provides a critical decision-making tool for educators, supporting more nuanced, student-specific instructional planning and remediation. In conclusion, Figure 3 reinforces the value of neutrosophic analysis in uncovering hidden uncertainties within educational classifications, advocating for uncertainty-aware pedagogy to address learning gaps systematically.

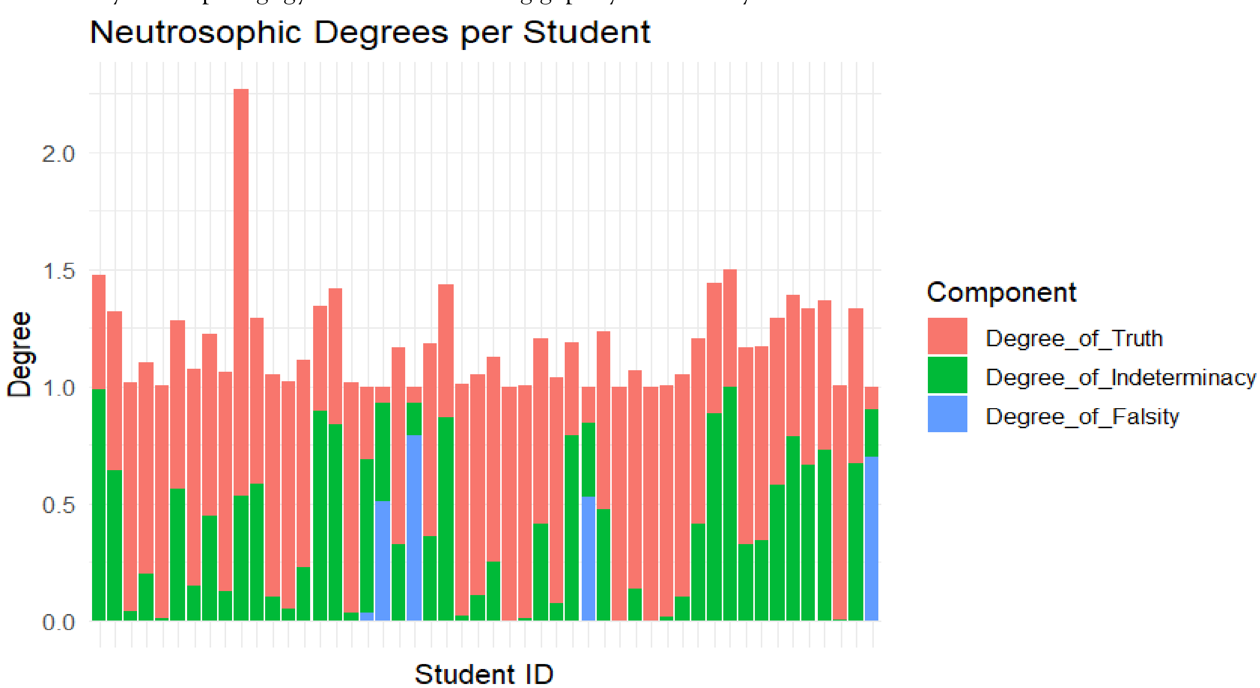

Figure 3: *Stacked Bar Chart Showing Distribution of Neutrosophic Degrees per Student for Depth of Knowledge Classifications*

Figure 4 presents a **boxplot of the distribution of neutrosophic components (truth, indeterminacy, and falsity) across students**, providing a comparative overview of classification certainty, uncertainty, and misclassification patterns in student assessments. The **Degree of Truth** shows the highest central tendency, with a median value close to **0.80** and an interquartile range spanning approximately **0.65 to 0.95**. This confirms that most students were classified with high certainty regarding their assigned Depth of Knowledge (DoK) levels. However, a few lower outliers indicate that some students were assessed with relatively weak certainty, reflecting potential classification ambiguity. The **Degree of Indeterminacy** demonstrates substantial variability. The median indeterminacy is approximately **0.35**, with the interquartile range extending from near **0.10** to about **0.60**. This wide spread indicates that while many students experience low uncertainty in classification, a notable portion exhibits considerable indeterminacy. The presence of upper outliers highlights students who face exceptionally high classification uncertainty, requiring attention. The **Degree of**

Falsity remains the lowest of the three components, with a median near **zero** and a compressed interquartile range. Despite its generally minimal contribution, occasional upper outliers suggest sporadic misclassifications, where student assessment outcomes deviate significantly from expected Depth of Knowledge levels. The overall assessment process predominantly results in high truth (certainty) degrees, with variable indeterminacy and minimal falsity. However, the presence of high indeterminacy for some students indicates cognitive ambiguity or assessment limitations. While the classification model effectively places most students with high confidence, a subset of students remains vulnerable to classification uncertainty. Sporadic instances of falsity highlight the need for improved diagnostic accuracy for certain profiles. Instructional interventions should not only focus on students with low certainty (truth) but also proactively address those exhibiting high degrees of indeterminacy, ensuring these uncertainties do not impede cognitive progression. From a policy standpoint, integrating uncertainty-aware assessment frameworks could improve the precision of cognitive classification and subsequent pedagogical responses. In conclusion, Figure 4 underscores the diagnostic power of neutrosophic analysis, enabling educators to move beyond binary classifications toward recognizing and responding to both uncertainty and misclassification risks inherent in student assessments.

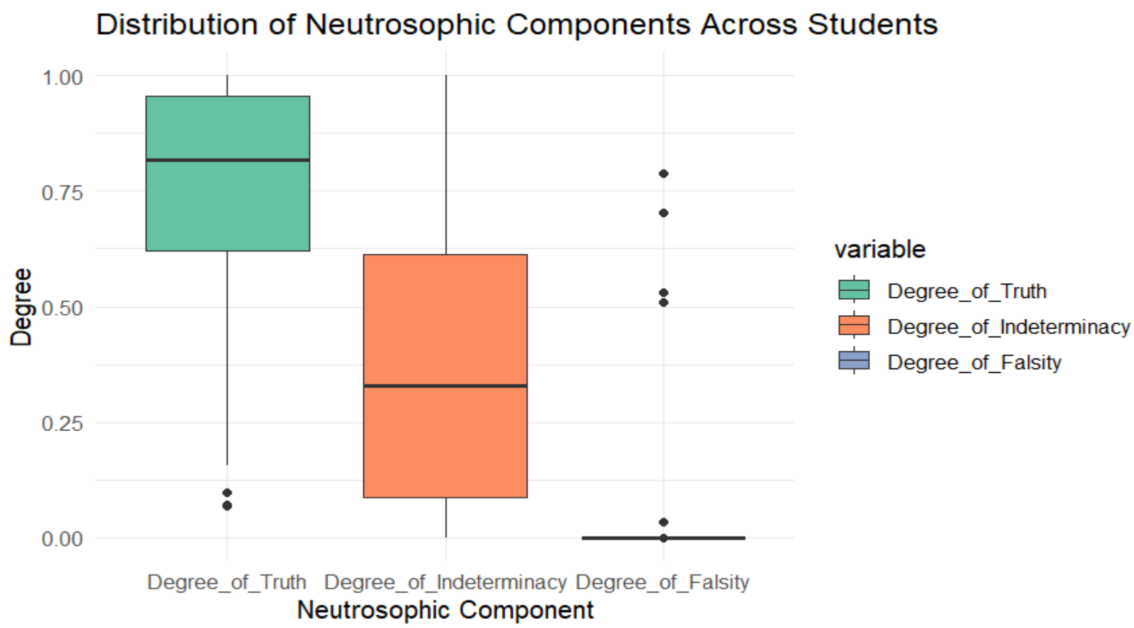

Figure 4: *Boxplots Comparing the Distributions of Truth, Indeterminacy, and Falsity Degrees in Student Classifications*

Figure 5 depicts the relationship between the **Degree of Truth** and the **Degree of Indeterminacy** for each student, with data points color-coded according to their assigned **Depth of Knowledge (DoK) Level**. Two reference lines are included: a vertical blue dashed line at a **Degree of Truth = 0.50**, and a horizontal red dashed line at a **Degree of Indeterminacy = 0.50**. These thresholds distinguish zones of high certainty and low uncertainty from areas where classification ambiguity is more pronounced. The scatterplot shows a clear inverse relationship between the two components: as the **Degree of Truth** increases, the **Degree of Indeterminacy** consistently decreases. Students with truth degrees exceeding 0.75 generally exhibit indeterminacy below 0.25, indicating strong and confident classification. These students are primarily clustered in the lower-right quadrant, representing a high-certainty, low-uncertainty zone. Conversely, students falling to the left of the **truth = 0.50** threshold often display indeterminacy levels above 0.50. These students populate the upper-left quadrant, signaling cases of high uncertainty and low classification confidence. It is notable that students from all four DoK levels, including Levels 3 and 4, appear in this uncertain zone, indicating that even higher cognitive classifications are not immune to assessment ambiguity. Classification confidence varies widely across students. While many achieve strong truth values with low uncertainty, a subset exhibits significant indeterminacy, regardless of DoK Level.The plot confirms that **classification uncertainty inversely mirrors certainty**, validating the neutrosophic modeling framework. Students positioned above the red dashed line or left of the blue dashed line represent cognitive profiles with ambiguous classifications requiring targeted assessment refinement or instructional intervention. Educational strategies should flag students within the high-indeterminacy, low-truth zone for additional support or reassessment. Assessment models must integrate uncertainty thresholds into diagnostic reporting, enabling instructors to recognize and address hidden ambiguities in student evaluations. In conclusion, Figure 5 demonstrates the practical value of neutrosophic analysis in visualizing classification reliability and diagnosing students whose DoK classifications are uncertain, guiding targeted instructional and assessment interventions.

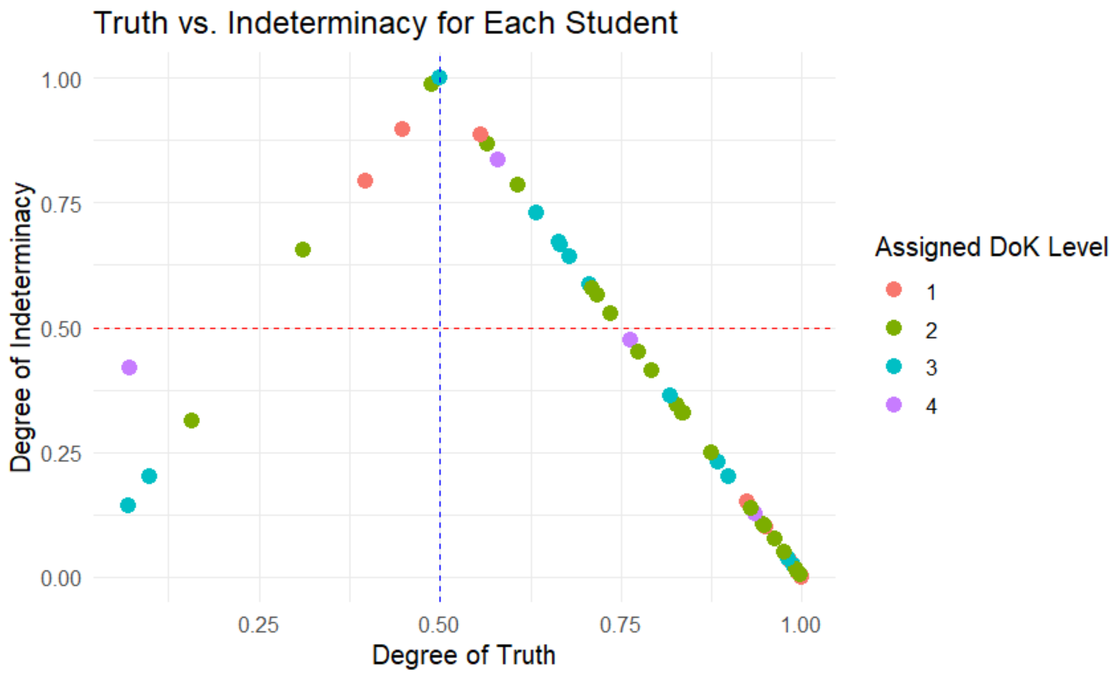

Figure 5: *Scatterplot of Degree of Truth Versus Degree of Indeterminacy with DoK Level Classifications and Uncertainty Threshold Indicators*

DISCUSSION

The findings underscore the robustness of current assessment frameworks in classifying lower and intermediate cognitive levels (DoK Levels 1 and 2). However, increased uncertainty in DoK Level 4 classifications reveals the limitations of deterministic models in capturing advanced cognitive complexity. Neutrosophic analysis provided valuable insights into classification confidence, highlighting hidden uncertainties not detected by traditional metrics. Students with high indeterminacy or non-trivial falsity degrees represent cognitively ambiguous profiles requiring diagnostic attention. The significant role of foundational mathematics (M1) as both a mediator and moderator confirms its central influence on cognitive development pathways, emphasizing the need to reinforce foundational competencies as a strategic intervention.

Policy Implications

Assessment frameworks should integrate uncertainty quantification mechanisms, such as neutrosophic analysis, to complement traditional deterministic models. This approach will enable educators to recognize and address classification ambiguities, particularly in advanced cognitive assessments.

Instructional policies must prioritize early identification and support for students with high indeterminacy or falsity indicators. Foundational mathematics should be strengthened as a key intervention focus to mitigate cognitive variability in higher DoK classifications.

Educational institutions should adopt uncertainty-aware diagnostic reporting systems, facilitating informed pedagogical decisions and individualized instructional interventions.

Major Findings

1. Current deterministic assessment frameworks classify lower and intermediate DoK levels reliably but struggle with advanced levels due to increased uncertainty.
2. Neutrosophic analysis effectively uncovers classification ambiguities, highlighting latent cognitive uncertainties and occasional misclassifications.
3. Foundational mathematics (M1) significantly influences DoK classification outcomes, operating as both mediator and moderator.
4. Classification uncertainties are not evenly distributed; advanced cognitive assessments are especially vulnerable to indeterminacy.

CONCLUSION

This study demonstrates the diagnostic and pedagogical value of integrating neutrosophic analysis with traditional assessment frameworks to enhance cognitive classification reliability in mathematics education. While current models perform well for basic and intermediate classifications, higher-order cognitive assessments require uncertainty-aware approaches to address inherent classification ambiguities. Foundational mathematics plays a pivotal role in moderating and mediating these outcomes. Policymakers and educators should integrate uncertainty measures into assessment and instructional strategies to ensure more precise cognitive classification and targeted educational support.

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