



A FUZZY INFERENCE FRAMEWORK FOR INTEGRATING PISA AND TIMSS INDICATORS IN THE GLOBAL EVALUATION OF MATHEMATICS EDUCATION

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Abstract

This study analyses the mathematical performance of 36 countries based on the 2022 PISA Mathematics scores and the 2023 TIMSS Grade 8 Mathematics scores. The objective of this study is to provide a more flexible and comprehensive evaluation of countries' performance by addressing the limitations of conventional crisp classification methods. To achieve this, a Mamdani fuzzy inference system is employed, where both PISA and TIMSS scores are modelled using fuzzy sets consisting of low, medium, and high categories. The fuzzy approach allows each country to be evaluated based on degrees of membership, enabling a more nuanced interpretation of performance levels. The results indicate that most countries fall into the medium performance category, while only a limited number are classified as high or low. Several countries are also identified as borderline cases, highlighting the presence of uncertainty and gradual transitions in performance levels. These findings demonstrate that the fuzzy approach provides a more realistic and flexible framework for analysing educational data, and it can serve as an alternative method to support more informed decision-making in education policy.

Keywords: Fuzzy Logic, Mamdani Method, PISA, TIMSS, Mathematical Performance

Abstrak

Penelitian ini menganalisis performa matematika 36 negara berdasarkan skor PISA Matematika tahun 2022 dan skor TIMSS Matematika Kelas 8 tahun 2023. Tujuan penelitian ini adalah untuk memberikan evaluasi performa negara yang lebih fleksibel dan komprehensif dengan mengatasi keterbatasan metode klasifikasi tegas (crisp) konvensional. Untuk mencapai tujuan tersebut, digunakan sistem inferensi fuzzy Mamdani, di mana skor PISA dan TIMSS dimodelkan menggunakan himpunan fuzzy yang terdiri dari kategori rendah, sedang, dan tinggi. Pendekatan fuzzy memungkinkan setiap negara dievaluasi berdasarkan derajat keanggotaan, sehingga menghasilkan interpretasi tingkat performa yang lebih mendalam. Hasil penelitian menunjukkan bahwa sebagian besar negara berada pada kategori performa sedang, sementara hanya sebagian kecil yang termasuk dalam kategori tinggi dan rendah. Beberapa negara juga teridentifikasi berada pada kondisi ambang (borderline), yang menunjukkan adanya ketidakpastian dan transisi bertahap dalam tingkat performa. Temuan ini menunjukkan bahwa pendekatan fuzzy memberikan kerangka analisis yang lebih realistis dan fleksibel dalam menganalisis data pendidikan, serta dapat menjadi metode alternatif dalam mendukung pengambilan keputusan yang lebih tepat dalam kebijakan pendidikan.

Kata kunci: Logika Fuzzy, Metode Mamdani, PISA, TIMSS, Performa Matematika

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INTRODUCTION

A country's education system can be evaluated based on its students' mathematical ability, which is essential for the advancement of science and technology and the development

of human resources. Human resources that are developed through mathematics education can think logically, analytically, and systemically (Niss & Højgaard, 2019), (Boesen et al., 2014). In today's knowledge-based economies, mathematics is vital for innovation, technology, and competitiveness. As a result, many international educational assessments have been created to evaluate students' mathematical achievements worldwide (Bolstad, 2023).

The Programme for International Student Assessment (PISA), conducted by the Organisation for Economic Co-operation and Development (OECD), is one of the most popular global international education assessment programs. This program evaluated 15-year-old students' competencies in different real-world situations. Within the domain of mathematics, PISA focuses on the idea of mathematical literacy, which is defined as a student's capacity to comprehend, employ, and interpret mathematics to resolve various issues facing society.

In addition to PISA, the Trends in International Mathematics and Science Study (TIMSS) is another international study often used to assess students' mathematical abilities. TIMSS is also organized by the International Association for the Evaluation of Educational Achievement (IEA). Unlike PISA, TIMSS places greater emphasis on students' mastery of mathematical concepts pertaining to the school curriculum. This study evaluates the mathematical achievement of students at the fourth and eighth grades, thus offering a glimpse into students' mastery of mathematical concepts at the primary and lower secondary education levels.

Although both studies provide very important information regarding the performance of mathematics education across countries, they have different measurement characteristics. **PISA** places greater emphasis on the ability to apply mathematics in real-life contexts, whereas **TIMSS** focuses more on the understanding of mathematical concepts taught in the school curriculum. In addition, the age groups of the participants assessed are also different. **TIMSS** evaluates students at earlier stages of education, while **PISA** assesses students who are at the final stage of compulsory basic education. These differences in approach may lead to evaluation results from the two studies that do not always present a consistent picture of a country's mathematics achievement (Yang et al., 2025), (Liu et al., 2024). Therefore, the simultaneous use of these two data sources can provide a more comprehensive picture of a country's mathematics education performance, both in terms of conceptual mastery and the ability to apply mathematics in real-life contexts.

On the other hand, most analyses of PISA and TIMSS results are still conducted using conventional approaches, such as comparing average scores or ranking countries. Such

approaches tend to be rigid and often fail to represent the complexity of educational systems. Previous studies have shown that the results of international large-scale assessments are frequently simplified into rankings or average scores, which may lead to oversimplified interpretations of educational performance (Sellar & Lingard, 2014), (Fischman et al., 2019). Students' achievement is influenced by many contextual factors related to learning environments, instructional quality, and educational systems (Liu et al., 2024), (Laukaityte et al., 2024).

In this context, **fuzzy logic** offers a more flexible alternative approach for the evaluation process. Fuzzy logic allows the representation of achievement levels that are not strictly defined and enables the integration of multiple assessment indicators simultaneously within an inference system. Through this approach, information obtained from various educational evaluation systems can be combined to produce a more comprehensive and representative measure of achievement.

Several previous studies have utilized fuzzy logic in various areas of educational evaluation due to its ability to handle uncertainty and integrate multiple assessment indicators within an inference system (Thanh Loan et al., 2024), (Pathak, 2025), (Pratama et al., 2021). Fuzzy-based models allow the representation of ambiguous concepts such as students' abilities and competencies more effectively than traditional evaluation methods (Ergin & Nasibov, 2025). However, many existing studies still rely on limited datasets or a small number of indicators when assessing student performance, indicating that more comprehensive approaches integrating multiple evaluation sources are still relatively limited.

Based on the above considerations, this study aims to develop a model for evaluating students' mathematics achievement across countries by integrating data from the **Programme for International Student Assessment (PISA)** and the **Trends in International Mathematics and Science Study (TIMSS)** using a fuzzy inference system based on the **Mamdani method**. The proposed model is expected to produce a more comprehensive evaluation measure for assessing the performance of mathematics education at the global level. Furthermore, the evaluation results are expected to provide a more holistic picture of the position and characteristics of a country's mathematics achievement in the international context, thereby serving as a useful reference for educational policymakers in evaluating and formulating strategies to improve the quality of mathematics education systems in their respective countries. The main contributions of this study are as follows:

1. It proposes a Mamdani fuzzy inference framework for integrating PISA and TIMSS

mathematics assessment data.

2. It combines two complementary dimensions of mathematics achievement, namely mathematical literacy and curriculum-based mathematical knowledge, into a unified evaluation model.
3. It provides a comprehensive country-level mathematics achievement index that reduces the limitations of relying on a single international assessment.
4. It demonstrates the applicability of fuzzy inference systems for synthesizing heterogeneous international educational assessment data.

This study is limited using only two indicators, namely PISA and TIMSS scores, which may not fully capture all aspects of educational quality. Additionally, the selection of membership functions and rules may influence the results of the fuzzy inference system.

METHODS

This study utilizes secondary data obtained from two international large-scale assessments, namely the Programme for International Student Assessment (PISA) 2022 (“Organization for Economic Co-Operation and Development (OECD) PISA 2022 Results,” 2023) and the Trends in International Mathematics and Science Study (TIMSS) (Ina V.S. Mullis et al., 2024). Data were accessed in **March 2026**.

The PISA dataset provides mathematics performance scores of 15-year-old students, while the TIMSS dataset measures mathematics achievement of Grade 8 students. These datasets are selected due to their global coverage and their complementary perspectives in assessing students’ mathematical abilities. The analysis was restricted to countries with complete data for both variables.

Prior to analysis, the data are pre-processed to ensure consistency and accuracy. The preprocessing steps include:

1. **Data cleaning**, by removing incomplete records and handling missing values.
2. **Data transformation**, ensuring that all numerical values are correctly formatted as decimal numbers.
3. **Data integration**, aligning country names to ensure proper merging between PISA and TIMSS datasets.

This study employs a fuzzy inference system based on the Mamdani method to evaluate the overall mathematical performance of students across countries. The Mamdani fuzzy IF–THEN rules enabling the modeling of human reasoning in complex decision-making processes.

The Mamdani approach applies to the minimum (min) operator for rule evaluation (logical AND) and the maximum (max) operator for aggregating the outputs of multiple rules (Selvachandran et al., 2021). The final crisp output is obtained through a defuzzification process, commonly using the centroid method, which determines the center of gravity of the aggregated fuzzy set (Kumari & Mohan, 2024). The fuzzy approach is chosen due to its ability to handle uncertainty and represent gradual transitions between performance levels. Two input variables are defined: PISA mathematics score and TIMSS mathematics score. Each input variable is represented using three linguistic terms: Low, Medium, and High.

The output variable represents the overall level of mathematical performance and is defined within a range of 0 to 100. It is categorized into three linguistic terms: Poor, Moderate, and Good.

The membership functions are constructed using triangular membership functions due to their simplicity and interpretability.

The general form of the triangular membership function is defined as:

$$\mu(x) = \begin{cases} 0, & x \leq a \text{ or } x \geq c \\ \frac{x-a}{b-a}, & a < x < b \\ \frac{c-x}{c-b}, & b \leq x < c \end{cases} \quad (1)$$

The parameters of the membership functions are determined based on commonly used score ranges in international assessments to represent different levels of mathematical performance.

The parameters of the triangular membership functions used in this study are summarized in Table 1. Each fuzzy set is defined by three parameters (a, b, c), representing the lower bound, peak, and upper bound of the membership function, respectively

Table 1. Parameters of Triangular Membership Functions

Variables	Linguistic Term	a	b	c
PISA	Low	350	350	420
	Medium	400	480	520
	High	500	580	580
TIMSS	Low	350	350	450
	Medium	420	500	550
	High	520	620	620
Output	Poor	0	0	50
	Moderate	30	50	70
	Good	50	100	100

The parameters of the membership functions are presented in Table 1. Based on these parameters, the corresponding membership functions for the input and output variables are visualized to provide a clearer representation of the fuzzy sets used in this study.

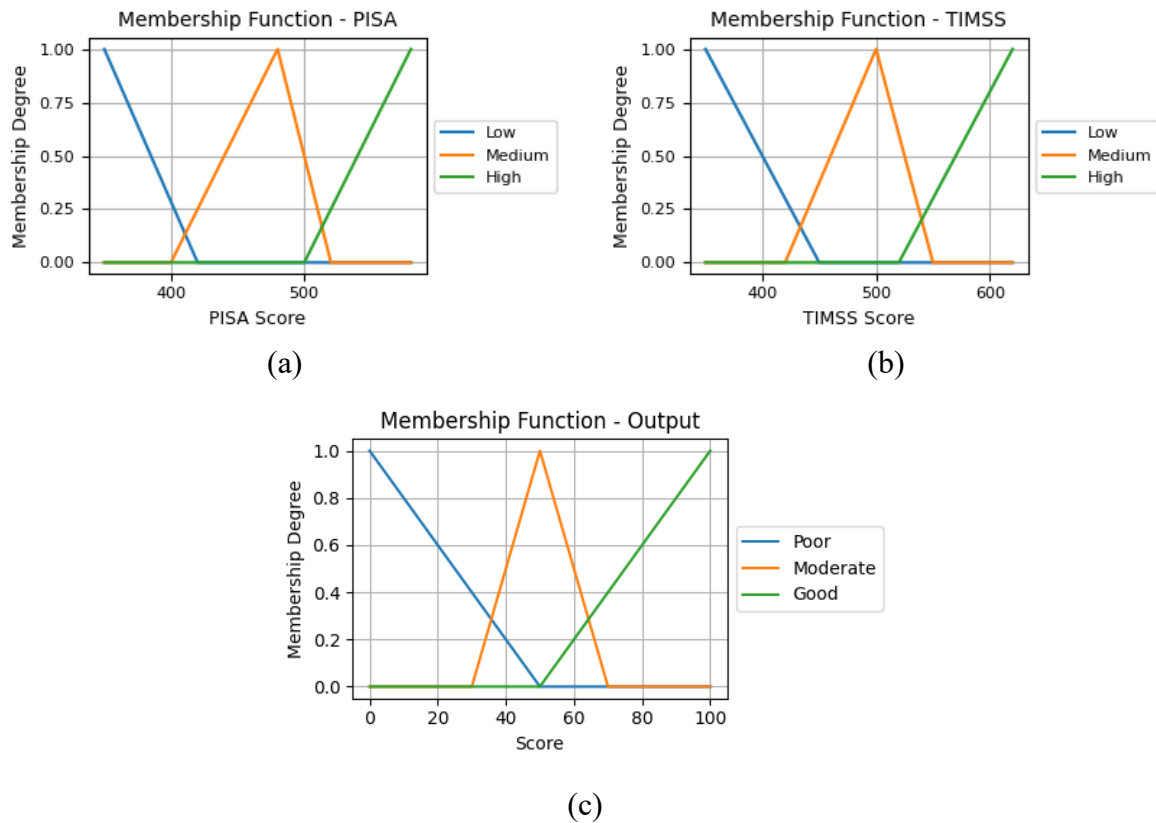


Figure 1. Membership functions for: (a) PISA mathematics scores, (b) TIMSS mathematics scores, and (c) output variable.

As shown in Figure 1, each variable is represented by three triangular membership functions corresponding to low, medium, and high categories. The overlapping regions indicate gradual transitions between performance levels.

A total of nine fuzzy rules is defined to model the relationship between PISA and TIMSS scores are represented in the following Table 2.

Table 2. Fuzzy rules

	Variables		
	PISA	TIMSS	Output
1	Low	Low	Poor
2	Low	Medium	Poor
3	Low	High	Moderate
4	Medium	Low	Poor
5	Medium	Medium	Moderate

6	Medium	High	Good
7	High	Low	Moderate
8	High	Medium	Good
9	High	High	Good

The Mamdani fuzzy inference method is applied, where the **minimum (min)** operator is used for rule evaluation (logical AND), and the **maximum (max)** operator is used for aggregation of rule outputs.

The final crisp output is obtained using the centroid method, defined as:

$$z^* = \frac{\int z \cdot \mu(z) dz}{\int \mu(z) dz} \quad (2)$$

This method calculates the centre of gravity of the aggregated fuzzy output to produce a representative numerical score.

RESULT AND DISCUSSION

This section presents the results of the fuzzy inference system applied to evaluate students' mathematical performance across countries using PISA and TIMSS data. The analysis aims to classify countries into three categories: poor, moderate, and good.

This study utilizes **data from 36 countries**, obtained in accordance with the sources and methodology described in Chapter 3. The data analyzed includes the 2022 PISA Mathematics scores and the 2023 TIMSS Grade 8 Mathematics scores. The complete dataset used in this study is presented on the table below.

Table 3. PISA and TIMSS scores

	Country	PISA math scores, 2022	Grade 8 mathematics TIMSS scores 2023
1	Australia	487.084	509
2	Austria	487.267	512
3	Azerbaijan	396.882	479
⋮	...	...	...
36	Uzbekistan	363.935	421

To facilitate data interpretation and identify regional patterns, the 2022 PISA Mathematics scores and the 2023 TIMSS Grade 8 Mathematics scores are visualized separately as world map charts, as shown in the figures below. The color gradients on the maps indicate the differences in scores among countries, allowing readers to quickly identify countries with high or low performance in these international assessments.

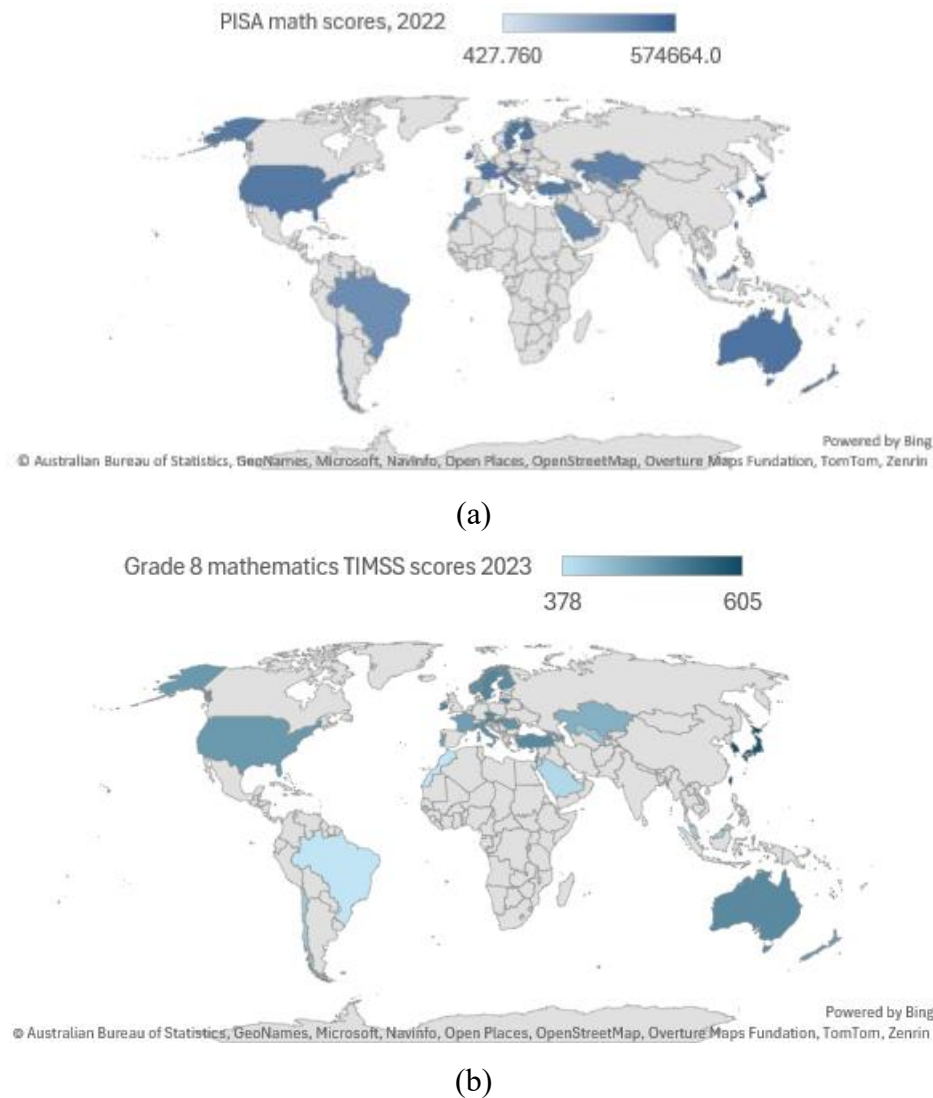


Figure 2. (a) PISA mathematics scores 2022, (b) TIMSS scores 2023

Based on the map visualizations, there is a clear variation in mathematics performance across countries. For instance, countries such as Singapore, Taiwan, Japan, and South Korea consistently achieve high scores in both PISA and TIMSS. In contrast, countries such as Morocco, Jordan, and Uzbekistan tend to exhibit lower performance levels.

However, the relationship between PISA and TIMSS scores is not perfectly consistent. Some countries, such as Turkey and Cyprus, show relatively moderate PISA scores but comparatively higher TIMSS scores, indicating discrepancies between the two assessments.

These findings suggest that a strict (crisp) classification such as categorizing countries as simply high or low performing, is insufficient to capture the complexity of the data. Several countries fall into intermediate or borderline categories, making their classification ambiguous. Clearer illustration is shown on the following scatter plot of Figure 3.

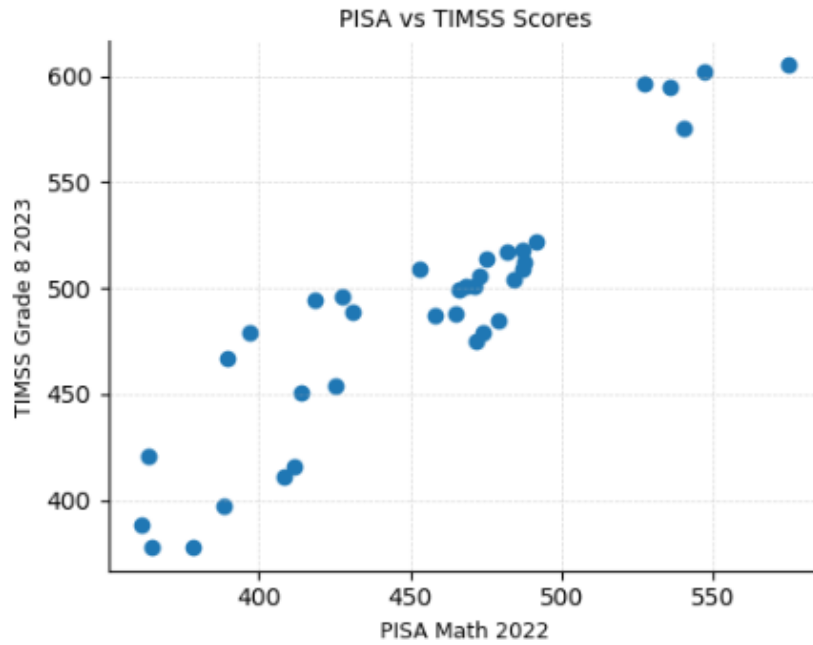


Figure 3. PISA vs TIMSS scatter plot

The scatter plot of PISA 2022 and TIMSS 2023 scores further illustrates the relationship between the two assessments. While a positive correlation can be observed, indicating that countries with higher PISA scores generally tend to achieve higher TIMSS scores, the distribution of data points is not perfectly linear. Several countries deviate from the general trend, indicating inconsistencies between the two assessments. These deviations highlight the presence of uncertainty and overlapping performance categories, particularly for countries located in the mid-range region.

This observation reinforces the need for a more flexible analytical approach. In this regard, fuzzy logic is particularly suitable, as it allows for gradual classification and can effectively handle ambiguous or borderline cases that cannot be addressed using traditional crisp methods. To obtain a more comprehensive evaluation of countries' mathematical performance, the PISA and TIMSS scores are further analyzed using a Mamdani fuzzy inference system. This approach allows each country to be assessed not only through crisp values but also through degrees of membership across multiple performance categories. The resulting fuzzy scores provide a more flexible representation of performance levels, particularly for countries that fall within intermediate or borderline regions. The results of this analysis are presented in the following table.

Table 4.

	Country	PISA	TIMSS	Fuzzy Score	Category
1	Australia	487.084	509	69.99991765	Medium
2	Austria	487.267	512	69.9999125	Medium
3	Azerbaijan	396.882	479	39.99989619	Low
⋮	...	...	...	...	...
36	Uzbekistan	363.935	421	39.99990345	Low

Let x and y denote the PISA and TIMSS scores, respectively. Each input variable is represented by three fuzzy sets, namely Low (L), Medium (M), and High (H), defined by their corresponding membership functions μ_L, μ_M, μ_H . The fuzzy inference process follows the Mamdani approach, where each rule is evaluated using the minimum operator:

$$\alpha_i = \min(\mu_{A_i}(x), \mu_{B_i}(y)), \quad (3)$$

where α_i denotes the firing strength of the i -th rule. The aggregated output is then obtained using the maximum operator over all activated rules. Finally, defuzzification is performed using the centroid method:

$$z^* = \frac{\sum \alpha_i z_i}{\sum \alpha_i} \quad (4)$$

where z_i represents the representative value of each output fuzzy set. The resulting crisp value z^* is used to determine the overall performance category of each country.

Based on the fuzzy evaluation results, the top 10 countries with the highest mathematical performance are as follows: Singapore, Taiwan, Hong Kong, Japan, South Korea, Ireland, Finland, Hungary, Italy, and Norway. These countries consistently demonstrate strong performance across both PISA and TIMSS assessments, resulting in high fuzzy scores and classification within the high-performance category. The following figure represents the top 10 countries based on fuzzy performance score.

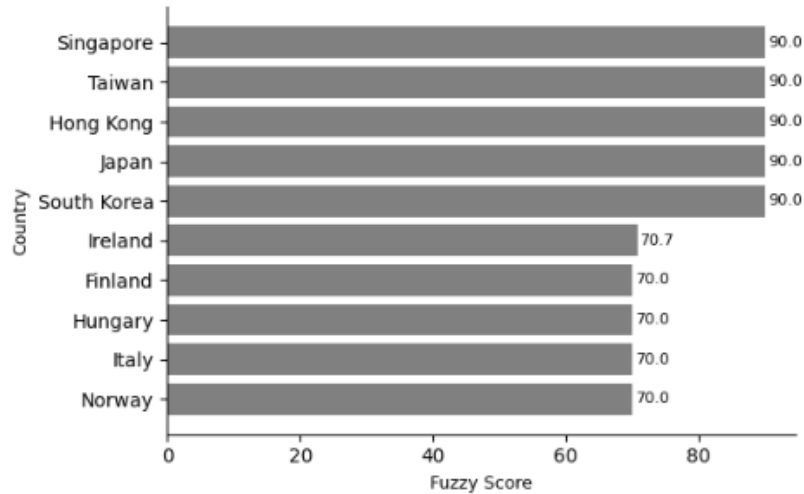


Figure 4. Top 10 countries based on fuzzy performance score

To further understand the overall pattern of countries' mathematical performance, the distribution of fuzzy classification results is analyzed. This distribution provides an overview of how countries are grouped into low, moderate, and high-performance categories based on the fuzzy inference system. By examining this distribution, it becomes possible to identify the dominance of certain performance levels and to better understand the general characteristics of the dataset.

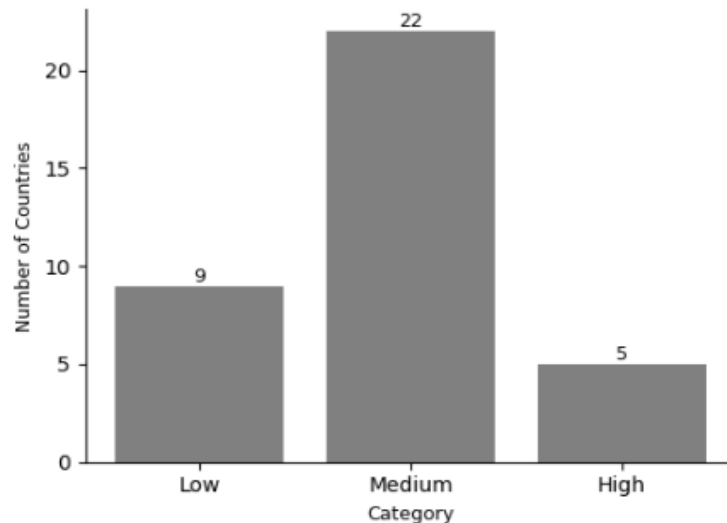


Figure 5. Distribution of mathematical performance categories

The distribution of mathematical performance categories reveals that most countries are classified in the medium category, while a smaller number fall into the high and low categories. This indicates that most countries exhibit moderate levels of performance in both PISA and TIMSS assessments. The presence of a considerable number of countries in the medium category suggests that many countries lie within transitional or borderline regions, where their performance cannot be distinctly categorized using crisp boundaries. Meanwhile, the high

category is dominated by a relatively small group of countries that consistently achieve strong results across both assessments, whereas the low category consists of countries with comparatively weaker performance. This distribution further supports the use of the fuzzy approach, as it effectively captures gradual differences in performance levels and accommodates the inherent uncertainty present in the data.

A few countries are grouped into the low-performance category, indicating comparatively lower achievement levels in both assessments. This finding suggests the need for a careful review of existing mathematics education policies and instructional strategies in these countries, particularly in terms of curriculum design, teaching approaches, and learning support systems.

The findings indicate that the proposed Mamdani fuzzy inference model provides a more comprehensive evaluation of national mathematics achievement by simultaneously incorporating students' performance in both PISA and TIMSS. This is consistent with previous studies showing that fuzzy inference systems can effectively integrate multiple assessment criteria under uncertainty, resulting in more flexible and interpretable evaluations than conventional score-based approaches. For example, Goyal et al. developed a fuzzy inference framework to integrate multiple course attainment indicators into program attainment assessment, demonstrating the effectiveness of fuzzy systems in combining heterogeneous educational performance indicators (Goyal et al., 2022). Similarly, Doz et al. proposed a fuzzy logic approach for combining students' grades with national assessment outcomes, concluding that fuzzy-based assessment can better accommodate uncertainty and linguistic evaluation than conventional grading systems (Doz et al., 2022).

Unlike previous studies, this research applies a Mamdani fuzzy inference system to integrate two international large-scale assessment programmes, namely PISA and TIMSS. Since PISA focuses on mathematical literacy in real-world contexts, whereas TIMSS emphasizes curriculum-based mathematical knowledge, combining both assessments provides a more balanced evaluation of mathematics achievement across countries than using either assessment alone.

The results also show that countries with consistently good performance in both assessments achieve higher fuzzy scores than countries performing well in only one assessment. This suggests that mathematics achievement should be viewed as a multidimensional construct rather than being assessed solely through average scores or international rankings. Therefore, the proposed fuzzy framework provides policymakers with

a more comprehensive basis for evaluating mathematics education performance and identifying areas for improvement. The researchers realized that future research involving sensitivity analysis of the fuzzy model would result in a comprehensive study.

CONCLUSION

This study evaluated the mathematical performance of 36 countries using PISA 2022 and TIMSS 2023 data through a Mamdani fuzzy inference system. The results indicate that most countries fall within the medium performance category, while only a limited number are classified as high or low.

The application of fuzzy logic successfully captures the uncertainty and gradual transitions in performance levels, particularly for countries in borderline conditions. Unlike conventional crisp classification methods, the fuzzy approach provides a more flexible and realistic evaluation by allowing partial membership across multiple categories.

Therefore, this study demonstrates that fuzzy logic is an effective method for analyzing multi-dimensional educational data and can serve as a valuable tool to support more informed and adaptive decision-making in education policy.

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