

RANKING STUDENTS PREFERENCES FOR MATHEMATICS MOBILE APPLICATIONS USING FUZZY GRADE MATRIX WITH DEGREE OF OPTIMISM AND STATISTICAL ANALYSIS APPROACH

(Pemerinkatan Keutamaan Pelajar Terhadap Aplikasi Mudah Alih Matematik Menggunakan Matriks Gred Fuzzy dengan Darjah Optimisme dan Pendekatan Analisis Statistik)

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ABSTRACT

Mathematics mobile applications have the potential to significantly enhance students' interest and learning in mathematics by taking advantage of the widespread use of smartphones and tablets. These applications offer interactive and engaging tools, such as real-time feedback, personalised learning paths, and access to a vast library of mathematical resources. This study explores students' preferences for different mathematics mobile applications by combining the fuzzy grade matrix with the degree of optimism and statistical analysis. The fuzzy grade matrix is particularly useful for addressing subjective opinions, uncertainty, and optimism, providing a flexible approach to managing complex decision-making processes. The process involves six steps: determining the importance of each criterion, assigning performance grades, constructing the grade matrix, calculating the overall scores, ranking the alternatives, and finally selecting the best options. The combined results show that functionality is the most important factor for students when choosing a mathematics mobile application, followed by efficiency and quality, with features being less critical. Symbolab was ranked as the top choice, followed by Photomath, Mathway, and Malmath, while Cymath was the least favoured. Complementing the fuzzy grade matrix, the statistical analysis further supports these findings, showing that Symbolab obtained the highest overall mean score (3.33) across all major criteria where Features (3.42), Efficiency (3.20), Quality (3.27), and Functionality (3.33) and followed by Photomath, Mathway, and Malmath, while Cymath recorded the lowest mean ratings. This integration of fuzzy evaluation with statistical validation provides a comprehensive and meaningful reflection of students' varied perspectives and preferences.

Keywords: fuzzy grade matrix; degree of optimism; mathematics mobile applications

ABSTRAK

Aplikasi matematik mudah alih berpotensi untuk meningkatkan minat dan pembelajaran pelajar dalam matematik dengan ketara melalui penggunaan meluas telefon pintar dan tablet. Aplikasi-aplikasi ini menawarkan alat pembelajaran yang interaktif dan menarik seperti maklum balas masa nyata, laluan pembelajaran diperibadikan serta akses kepada perpustakaan sumber matematik yang luas. Kajian ini meneroka keutamaan pelajar terhadap pelbagai aplikasi matematik dengan menggabungkan kaedah matriks gred kabur dengan darjah optimisme dan analisis statistik. Kaedah matriks gred kabur amat berguna dalam menangani pendapat subjektif, ketidakpastian dan tahap optimisme, serta menyediakan pendekatan yang fleksibel dalam mengurus proses membuat keputusan yang kompleks. Proses ini melibatkan enam langkah iaitu menentukan kepentingan setiap kriteria, menetapkan gred prestasi, membina matriks gred, mengira markah keseluruhan, menyusun kedudukan alternatif dan akhirnya memilih pilihan terbaik. Hasil gabungan menunjukkan bahawa fungsi merupakan faktor paling penting bagi pelajar dalam memilih aplikasi matematik, diikuti oleh kecekapan dan kualiti, manakala ciri tambahan adalah kurang kritikal. Symbolab dinilai sebagai pilihan utama, diikuti oleh Photomath, Mathway dan Malmath, manakala Cymath merupakan yang paling kurang

digemari. Analisis statistik yang melengkapi kaedah matriks gred kabur turut menyokong penemuan ini, menunjukkan bahawa Symbolab memperoleh skor min keseluruhan tertinggi (3.33) bagi semua kriteria utama — Ciri-ciri (3.42), Kecekapan (3.20), Kualiti (3.27) dan Fungsi (3.33) — diikuti oleh Photomath, Mathway dan Malmath, manakala Cymath mencatat skor terendah. Penggabungan antara penilaian kabur dan pengesahan statistik ini memberikan gambaran yang menyeluruh dan bermakna terhadap pelbagai perspektif dan keutamaan pelajar.

Kata kunci: matriks gred kabur; darjah optimisme; aplikasi matematik mudah alih

1. Introduction

Educational mathematics mobile applications, particularly those designed for mathematics learning, have become essential tools in modern education. They promote independent and interactive learning by offering features such as graphing tools, step-by-step problem solving, and immediate feedback that help students verify answers and correct errors efficiently (Drigas & Pappas 2015). Integrating technology in mathematics instruction is recognised as crucial to improving students' engagement and understanding (Fabian *et al.* 2018). However, not all mathematics applications provide the same level of quality or functionality. Their effectiveness often depends on usability, processing speed, and interface design. With numerous options available, students may struggle to select the most suitable application for their learning needs. Evaluating these applications involves subjective judgments that are frequently uncertain or imprecise. To address this issue, the present study applied the Fuzzy Grade Matrix (FGM) with a degree of optimism to systematically evaluate and rank students' preferences for selected mathematics mobile applications.

The fuzzy approach effectively manages uncertainty and incorporates multiple decision-makers' perspectives. A statistical analysis is also conducted on the same dataset to compare and validate the results obtained from the fuzzy method. This combined fuzzy–statistical approach provides a comprehensive evaluation of students' preferences for mathematics mobile applications emphasizing key decision factors such as functionality, efficiency, quality, and features. Previous studies have also adopted Fuzzy Set Theory to identify decision factors in evaluating mobile learning applications. For instance, Başaran and El Homsy (2022) applied the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to assess the most effective mathematics mobile applications, while more recent works have integrated fuzzy logic with empirical analysis to improve accuracy and adaptability (Anbarkhan 2023; Al-Gerafi *et al.* 2024). Nonetheless, these studies typically applied fuzzy models independently or used statistical tools solely for validation. The present study advances this line of inquiry by jointly employing fuzzy and statistical analyses to ensure consistency, robustness, and practical insight into students' preferences for mathematics mobile applications.

2. Methodology

This study applied two main analytical approaches which are the Fuzzy Grade Matrix (FGM) and descriptive statistical analysis. The study involved 100 undergraduate students from a higher education institution located in the Klang Valley. Students' preferences for mathematics mobile applications were analysed primarily using the fuzzy grade matrix based on the degree of optimism, while statistical analysis was later applied for comparative purposes. The fuzzy grade matrix was adopted as the main analytical framework to address uncertainty and subjectivity in decision-making. This method involves determining the weight of each criterion,

computing the grades for each sub-criterion, constructing the grade matrix, calculating the overall grade vector, and ranking the alternatives to identify the most preferred mathematics mobile application.

In this study, students were asked to assess their preferences for five selected mathematics mobile applications, namely Symbolab, Photomath, Mathway, Malmath, and Cymath. Each participant completed an online questionnaire designed to evaluate the relevance and performance of these applications according to a set of established criteria and sub-criteria. The decision structure and evaluation components are presented in Figure 1 and Table 1, respectively. Based on Table 1, the criterion features (X_1) has three sub-criteria which are approachability (X_{11}), discoverable (X_{12}) and well-organised (X_{13}). The sub-criteria approachability (X_{11}) refers to ease of initial use, discoverability (X_{12}) refers to ease of finding features, and well-organised (X_{13}) refers to interface clarity. For the criterion efficiency (X_2), it also has three sub-criteria which are availability (X_{21}), security (X_{22}) and runtime (X_{23}). Availability (X_{21}) refers to accessibility, security (X_{22}) refers to data protection, and runtime (X_{23}) refers to system responsiveness. For the criterion quality (X_3), the sub-criteria effectiveness (X_{31}) refers to task accuracy, error handling (X_{32}) refers to the ability to manage errors, and user-friendly (X_{33}) refers to ease of interaction. For functionality (X_4), the sub-criteria appropriateness (X_{41}) refers to suitability for learning, learnability (X_{42}) refers to ease of learning to use the application, and reliability (X_{43}) refers to consistency of performance. These definitions are adopted from previous studies on mobile application evaluation by Başaran and El Homsy (2022) and Al-Gerafi *et al.* (2024).

For the statistical analysis, the same dataset was analysed to examine the consistency of findings with the fuzzy grade matrix approach. The mean values of students' preferences were calculated based on the proportion of mathematics mobile applications currently used. The mean score was calculated for each item. The mean score represents the average response of all participants and is computed by summing all individual scores and dividing by the total number of respondents. Data visualisation and analysis were performed using R programming packages such as *ggplot2* and *tidyverse*. The mean scores for each criterion and sub-criterion were then compared across the applications to determine the actual usage patterns and preference trends among students.

Table 1: The main criteria and sub-criteria factors affecting selection

Main criteria	Sub-criteria
Features (X_1)	(X_{11}) Approachability
	(X_{12}) Discoverable
	(X_{13}) Well-organised
Efficiency (X_2)	(X_{21}) Availability
	(X_{22}) Security
	(X_{23}) Runtime
Quality (X_3)	(X_{31}) Effectiveness
	(X_{32}) Error handling
	(X_{33}) User-friendly
Functionality (X_4)	(X_{41}) Appropriateness
	(X_{42}) Learnability
	(X_{43}) Reliability

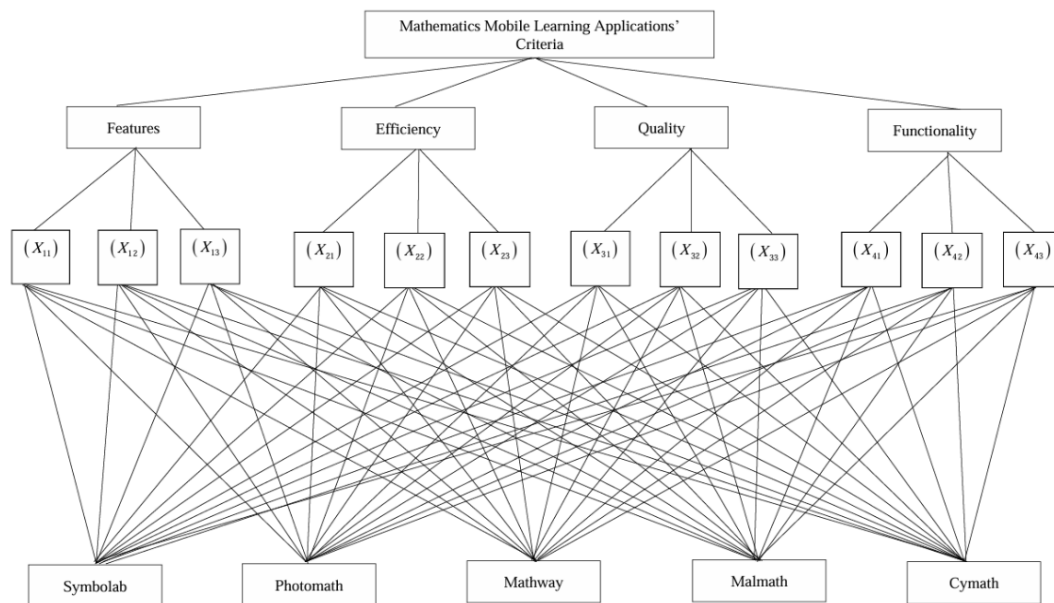


Figure 1: The decision hierarchical structure

Table 2 shows the fuzzy linguistic variable and fuzzy membership functions for each criterion weight (Kabir & Hasin 2012), while Table 3 shows the linguistic variables and triangular fuzzy membership functions for ratings of alternatives for each sub-criterion (Türker *et al.* 2019).

Table 2: Linguistic variables and fuzzy membership functions for the weight of criteria (Kabir & Hasin 2012)

Linguistic character	Fuzzy triangular membership functions
Very Low (VL)	(0, 0, 0.1)
Low (L)	(0, 0.1, 0.3)
Medium Low (ML)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
Medium High (MH)	(0.5, 0.7, 0.9)
High (H)	(0.7, 0.9, 1)
Very High (VH)	(0.9, 1, 1)

Table 3: Linguistic variables and triangular fuzzy membership functions for ratings of alternatives for each sub-criterion (Türker *et al.* 2019)

Linguistic character	Fuzzy triangular membership functions
Very Good (VG)	(9, 10, 10)
Good (G)	(7, 9, 10)
Medium Good (MG)	(5, 7, 9)
Fair (F)	(3, 5, 7)
Medium Poor (MP)	(1, 3, 5)
Poor (P)	(0, 1, 3)
Very Poor (VP)	(0, 0, 1)

Six steps are involved in the fuzzy grade matrix with degree of optimism as follows:

Step 1: Determine each criterion's fuzzy weight. The fuzzy weight $\tilde{w}_i$ of each criterion is determined for K decision-makers using an aggregated fuzzy assessment, as defined follows:

$$\tilde{w}_i = \frac{\sum_{k=1}^K \tilde{w}_i^k}{K} \quad (1)$$

where $\tilde{w}_i^k$ denotes the significance weight of the k -th decision-maker, and K denotes the number of decision-makers. The fuzzy weighted vector criteria are written as follows:

$$\tilde{W} = [\tilde{w}_1 \tilde{w}_2 \tilde{w}_3 \dots \tilde{w}_i]^T \quad (2)$$

Step 2: Determine the fuzzy grade for every sub-criterion. The aggregated fuzzy assessment is used to figure out the fuzzy grade $\tilde{g}_{ij,m}$ for every sub-criterion of each alternative or option. The aggregated fuzzy assessment is defined as follows:

$$\tilde{g}_{ij,m} = \frac{\sum_{k=1}^K \tilde{x}_{ij,m}^k}{K} \quad (3)$$

where $\tilde{x}_{ij,m}^k$ is the rating of sub-criterion X_{ij} for alternative m by the k -th decision maker.

Step 3: Determine the fuzzy grade of each alternative with respect to each criterion. For p sub-criteria of criterion X_i , the fuzzy grade $\tilde{g}_{mi}$ alternative m with respect to criterion X_i is defined as

$$\tilde{g}_{mi} = \frac{\sum_{j=1}^p \tilde{g}_{ij,m}}{p} \quad (4)$$

The fuzzy grade matrix $\tilde{G}$ is constructed as follows:

$$\tilde{G} = \begin{pmatrix} \tilde{g}_{11} & \tilde{g}_{12} & \cdots & \tilde{g}_{1k} \\ \tilde{g}_{21} & \tilde{g}_{22} & \cdots & \tilde{g}_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{g}_{n1} & \tilde{g}_{n2} & \cdots & \tilde{g}_{nk} \end{pmatrix}$$

where n is the number of alternatives, k is the number of criteria, and $\tilde{g}_{mi}$ denotes the fuzzy grade of the m -th alternative A_m with respect to the i -th criterion $1 \leq m \leq n, 1 \leq i \leq k$.

Step 4: Determine the total of the fuzzy grades $\tilde{R}$, using the following:

$$\tilde{R} = \tilde{G} \otimes \tilde{W} = \begin{pmatrix} \tilde{g}_{11} & \tilde{g}_{12} & \cdots & \tilde{g}_{1k} \\ \tilde{g}_{21} & \tilde{g}_{22} & \cdots & \tilde{g}_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{g}_{n1} & \tilde{g}_{n2} & \cdots & \tilde{g}_{nk} \end{pmatrix} \otimes \begin{pmatrix} \tilde{w}_1 \\ \tilde{w}_2 \\ \vdots \\ \tilde{w}_k \end{pmatrix} = \begin{pmatrix} \tilde{R}_1 \\ \tilde{R}_2 \\ \vdots \\ \tilde{R}_n \end{pmatrix} \quad (5)$$

where $1 \leq i \leq n$ and $\tilde{R}_i$ represents the total fuzzy grade of the i -th alternative A_i .

Step 5: Rank the fuzzy numbers using the left and right integral values approach (Liou & Wang 1992), which accounted the perspectives of decision-makers based on the optimism index. Given a trapezoidal fuzzy number $A(a, b, c, d)$ with the membership function as follows:

$$f_A(x) = \begin{cases} \frac{x-a}{b-a} & , a \leq x \leq b \\ 1 & , b \leq x \leq c \\ \frac{x-d}{c-d} & , c \leq x \leq d \\ 0 & , otherwise \end{cases} \quad (6)$$

Hence, $f_A^L(x) = \frac{x-a}{b-a}$ and $f_A^R(x) = \frac{x-d}{c-d}$. For the inverse functions $f_A^L(x)$ and $f_A^R(x)$ which are $g_A^L(x) = a + (b-a)y$ and $g_A^R(x) = d + (c-d)y$, where $y \in [0,1]$. Therefore,

$$I_L(A) = \int_0^1 g_A^L(y) dy = \int_0^1 [a + (b-a)y] dy = \frac{1}{2}(a+b) \quad (7)$$

$$I_R(A) = \int_0^1 g_A^R(y) dy = \int_0^1 [d + (c-d)y] dy = \frac{1}{2}(c+d) \quad (8)$$

Provided $\beta \in [0,1]$, the integral sum value can be determined by

$$I_T^\beta = \frac{1}{2}[\beta(c+d) + (1-\beta)(a+b)] \quad (9)$$

Therefore, for a triangular fuzzy number with $b=c$, and $\beta \in [0,1]$, the left integral, the right integral and the total integral are given as follows:

$$I_L(A) = \frac{1}{2}(a+b), \quad I_R(A) = \frac{1}{2}(b+d) \quad \text{and} \quad I_T^\beta = \frac{1}{2}[\beta(b+d) + (1-\beta)(a+b)] \quad (10)$$

where I_T^β represents as $R(\tilde{A}_i)$, with $\beta=0$ means pessimistic, $\beta=0.5$ means neutral, $\beta=1$ means optimistic.

Step 6: Ranking the fuzzy numbers based on the following conditions:

- (1) If $R(\tilde{A}_i) < R(\tilde{A}_j)$, then $\tilde{A}_i < \tilde{A}_j$,
- (2) If $R(\tilde{A}_i) = R(\tilde{A}_j)$, then $\tilde{A}_i \approx \tilde{A}_j$, and
- (3) If $R(\tilde{A}_i) > R(\tilde{A}_j)$, then $\tilde{A}_i > \tilde{A}_j$

where $R(\tilde{A}_i)$ refers to I_T^β in Equation (2.10).

3. Implementation

This section consists of two main parts: the Fuzzy Grade Matrix (FGM) analysis and the descriptive statistical analysis. The FGM approach was implemented to determine the relative importance and ranking of mathematics mobile applications based on students' perceptions, while the statistical analysis was applied to validate and compare these results quantitatively. Together, these methods provide both a fuzzy-based and a data-driven evaluation framework, aligning with the study's aim of integrating mathematical modelling with empirical analysis.

This study was conducted to ascertain which mobile mathematics applications received the highest rating from respondents. The first part explains the step-by-step procedure of the Fuzzy Grade Matrix (FGM) with degree of optimism, and the second part presents the statistical analysis, which summarises the descriptive measures (means and proportions) of students' preferences for each criterion and sub-criterion.

Step 1: Determine the fuzzy weight of each criterion.

100 decision-makers K_1, K_2, K_3 , and K_{100} rated the importance of each criterion X_1 (Features), X_2 (Efficiency), X_3 (Quality), and X_4 (Functionality). Tables 4 and 5 show the linguistic variables and triangular fuzzy numbers for the weight of criteria.

Table 1: Linguistic variables for weight of criteria

Decision Maker	Criteria			
	X_1	X_2	X_3	X_4
K_1	VL	VL	VL	VL
K_2	VH	VH	VH	VH
K_3	MH	VH	VH	VH
K_4	VH	VH	VH	VH
K_5	VH	VH	VH	VH
K_6	VH	VH	VH	VH
K_7	VH	VH	VH	VH
K_8	VH	VH	VH	VH
K_9	MH	ML	ML	MH
K_{10}	VH	VH	VH	VH
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
K_{95}	MH	VH	MH	MH
K_{96}	VH	VH	VH	VH
K_{97}	MH	ML	MH	MH
K_{98}	MH	VH	VH	VH
K_{99}	ML	VH	VH	VH
K_{100}	VH	VH	MH	VH

Table 2: Weight of criteria in triangular fuzzy number

Decision Maker	Criteria			
	X_1	X_2	X_3	X_4
K_1	(0,0,0.1)	(0,0,0.1)	(0,0,0.1)	(0,0,0.1)
K_2	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)
K_3	(0.5,0.7,0.9)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)
K_4	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)
K_5	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)
K_6	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)
K_7	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)
K_8	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)
K_9	(0.5,0.7,0.9)	(0.1,0.3,0.5)	(0.1,0.3,0.5)	(0.5,0.7,0.9)
K_{10}	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
K_{95}	(0.5,0.7,0.9)	(0.9,1,1)	(0.5,0.7,0.9)	(0.5,0.7,0.9)
K_{96}	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)
K_{97}	(0.5,0.7,0.9)	(0.1,0.3,0.5)	(0.5,0.7,0.9)	(0.5,0.7,0.9)
K_{98}	(0.5,0.7,0.9)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)
K_{99}	(0.1,0.3,0.5)	(0.9,1,1)	(0.9,1,1)	(0.9,1,1)
K_{100}	(0.9,1,1)	(0.9,1,1)	(0.5,0.7,0.9)	(0.9,1,1)

Based on Equation (2.1) with $K=100$, and the triangular fuzzy number of weight of criteria in Table 5, the fuzzy grade $\tilde{w}_i$ for criterion X_2 is given as follows:

$$\tilde{w}_2 = \frac{(0,0,0.1)+(0.9,1,1)+(0.9,1,1)+\dots+(0.9,1,1)+(0.9,1,1)+(0.9,1,1)}{100}$$

$$\tilde{w}_2 = \frac{(72.9, 85.6, 91.9)}{100} = (0.729, 0.856, 0.919)$$

In similar manner, the fuzzy grade $\tilde{w}_i$ for criteria X_1, X_3 and X_4 can be obtained.

Therefore, the fuzzy weighted vector $\tilde{W}$ for four criteria is represented as follows:

$$\tilde{W} = \begin{pmatrix} \tilde{w}_1 \\ \tilde{w}_2 \\ \tilde{w}_3 \\ \tilde{w}_4 \end{pmatrix} = \begin{pmatrix} (0.623, 0.770, 0.876) \\ (0.729, 0.856, 0.919) \\ (0.682, 0.826, 0.919) \\ (0.770, 0.904, 0.956) \end{pmatrix} \quad (11)$$

Step 2: Determine the fuzzy grade for each sub-criterion.

Table 6 shows the rating of alternatives for each sub-criterion by the first decision maker (K_1).

Table 3: Ratings of Alternatives for each sub-criterion by the first decision maker (K_1)

Criteria	Sub-criteria	Symbolab	Photomath	Mathway	Malmath	Cymath
X_1	X_{11}	VG	G	VG	G	G
	X_{12}	VG	VG	VG	G	VG
	X_{13}	VG	G	G	MG	MG
X_2	X_{21}	VG	G	G	G	G
	X_{22}	G	G	MG	MG	MG
	X_{23}	G	G	G	MG	MG
X_3	X_{31}	VG	G	VG	G	G
	X_{32}	G	G	G	MG	MG
	X_{33}	G	G	G	G	G
X_4	X_{41}	G	G	G	G	G
	X_{42}	VG	VG	G	MG	G
	X_{43}	VG	VG	G	G	G

Table 7 shows the linguistic variables and triangular fuzzy numbers for rating of alternatives for alternative Symbolab (A_1) based on sub-criterion X_{11} .

Table 7: Linguistic variables and triangular fuzzy numbers for rating of alternatives for alternative Symbolab (A_1) based on sub-criterion X_{11}

Decision maker	Sub- criteria	Linguistic variable	Triangular Fuzzy Numbers
K_1	X_{11}	VG	(9,10,10)
K_2		VG	(9,10,10)
K_3		F	(3,5,7)
K_4		F	(3,5,7)
K_5		F	(3,5,7)
K_6		MG	(5,7,9)
K_7		VG	(9,10,10)
K_8		VG	(9,10,10)
K_9		G	(7,9,10)
K_{10}		G	(7,9,10)

Table 7 (Continued)		
$\vdots$	$\vdots$	$\vdots$
K_{95}	G	(7,9,10)
K_{96}	G	(7,9,10)
K_{97}	F	(3,5,7)
K_{98}	G	(7,9,10)
K_{99}	F	(3,5,7)
K_{100}	MG	(5,7,9)

Based on Equation (2.3) and ratings of alternative (Symbolab A_1) for sub-criterion X_{11} in Table 7, the fuzzy grade $\tilde{g}_{11,1}$ (which is the aggregated of ratings for alternative (Symbolab A_1) based on sub-criterion X_{11}) is given as follows:

$$\tilde{g}_{11,1} = \frac{\sum_{k=1}^{100} \tilde{x}_{11,1}^k}{100}$$

$$\tilde{g}_{11,1} = \frac{(9,10,10) + (9,10,10) + (3,5,7) + \dots + (7,9,10) + (3,5,7) + (5,7,9)}{100} = \frac{(631, 804, 915)}{100}$$

$$\tilde{g}_{11,1} = (6.31, 8.04, 9.15)$$

In similar manner, the fuzzy grade $\tilde{g}_{ij,m}$ for each alternative A_m based on each sub-criteria X_{ij} is presented in Table 8.

Table 8: The fuzzy grade of each alternative relative to every sub-criterion

Criteria	Symbolab	Photomath	Mathway	Malmath	Cymath
sub-criteria	(A_1)	(A_2)	(A_3)	(A_4)	(A_5)
X_1	X_{11} (6.31, 8.04, 9.15)	(6.84, 8.54, 9.51)	(6.03, 7.88, 9.14)	(5.13, 7.08, 8.63)	(5.22, 7.15, 8.68)
	X_{12} (7.56, 9.08, 9.77)	(7.12, 8.71, 9.54)	(6.81, 8.49, 9.49)	(5.74, 7.67, 9.10)	(5.76, 7.66, 9.07)
	X_{13} (7.17, 8.82, 9.67)	(7.02, 8.75, 9.68)	(6.56, 8.38, 9.53)	(5.86, 7.80, 9.22)	(5.79, 7.73, 9.17)
X_2	X_{21} (7.17, 8.79, 9.65)	(6.90, 8.60, 9.57)	(6.39, 8.18, 9.36)	(5.73, 7.65, 9.08)	(5.76, 7.66, 9.08)
	X_{22} (7.08, 8.77, 9.67)	(6.76, 8.55, 9.60)	(6.48, 8.29, 9.46)	(5.96, 7.86, 9.22)	(6.00, 7.90, 9.23)
	X_{23} (7.20, 8.84, 9.67)	(6.97, 8.67, 9.60)	(6.69, 8.45, 9.52)	(6.04, 7.94, 9.23)	(6.08, 7.99, 9.31)
X_3	X_{31} (7.32, 8.93, 9.72)	(7.04, 8.70, 9.57)	(6.67, 8.39, 9.41)	(5.98, 7.89, 9.25)	(6.12, 8.01, 9.32)
	X_{32} (6.49, 8.25, 9.37)	(6.21, 8.03, 9.24)	(5.99, 7.86, 9.24)	(5.65, 7.57, 9.02)	(5.68, 7.61, 9.09)
	X_{33} (7.29, 8.90, 9.72)	(7.24, 8.88, 9.70)	(6.67, 8.39, 9.46)	(6.13, 7.97, 9.27)	(6.26, 8.04, 9.27)
X_4	X_{41} (7.08, 8.77, 9.70)	(6.87, 8.60, 9.60)	(6.59, 8.36, 9.50)	(6.20, 8.06, 9.36)	(6.10, 7.99, 9.33)
	X_{42} (7.41, 8.97, 9.73)	(7.16, 8.85, 9.72)	(6.83, 8.59, 9.61)	(6.40, 8.25, 9.47)	(6.47, 8.26, 9.42)
	X_{43} (7.26, 8.88, 9.72)	(7.12, 8.78, 9.66)	(6.74, 8.49, 9.57)	(6.23, 8.11, 9.39)	(6.30, 8.17, 9.43)

Step 3: Determine the fuzzy grade of each alternative with respect to each criterion.

Based on Table 8, the fuzzy grade $\tilde{g}_{mi}$ of each alternative with respect to each criterion can be determined by Eq. (2.4). To obtain the fuzzy grade $\tilde{g}_{11}$ of alternative A_1 with respect to criteria X_1 is shown as follows:

$$\tilde{g}_{11} = \frac{(\tilde{g}_{11,1} + \tilde{g}_{12,1} + \tilde{g}_{13,1})}{3} = \frac{(6.31, 8.04, 9.15) + (7.56, 9.08, 9.77) + (7.17, 8.82, 9.67)}{3}$$

$$\tilde{g}_{11} = (7.01, 8.65, 9.53)$$

In similar manner, we obtained $\tilde{g}_{mi}$ for $\forall m = 1, 2, 3, 4, 5$ and $\forall i = 1, 2, 3, 4$. Hence, the fuzzy grade matrix $\tilde{G}$ is presented as follows:

$$\tilde{G} = \begin{matrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \end{matrix} \begin{pmatrix} X_1 & X_2 & X_3 & X_4 \\ (7.01, 8.65, 9.53) & (7.15, 8.80, 9.66) & (7.03, 8.69, 9.60) & (7.25, 8.87, 9.72) \\ (6.99, 8.67, 9.58) & (6.88, 8.61, 9.59) & (6.83, 8.54, 9.50) & (7.05, 8.74, 9.66) \\ (6.47, 8.25, 9.37) & (6.52, 8.31, 9.45) & (6.44, 8.21, 9.37) & (6.72, 8.48, 9.56) \\ (5.58, 7.52, 8.98) & (5.91, 7.81, 9.18) & (5.92, 7.81, 9.18) & (6.28, 8.14, 9.41) \\ (5.59, 7.51, 8.97) & (5.59, 7.85, 9.21) & (6.02, 7.89, 9.23) & (6.29, 8.14, 9.39) \end{pmatrix} \quad (12)$$

Step 4: Calculate total fuzzy grade.

Based on Equations (2.5), (3.1) and (3.2), the total fuzzy grade vector $\tilde{R}$ is obtained as follows:

$$\begin{pmatrix} \tilde{R}_1 \\ \tilde{R}_2 \\ \tilde{R}_3 \\ \tilde{R}_4 \\ \tilde{R}_5 \end{pmatrix} = \begin{pmatrix} \tilde{g}_{11} & \tilde{g}_{12} & \tilde{g}_{13} & \tilde{g}_{14} \\ \tilde{g}_{21} & \tilde{g}_{22} & \tilde{g}_{23} & \tilde{g}_{24} \\ \tilde{g}_{31} & \tilde{g}_{32} & \tilde{g}_{33} & \tilde{g}_{34} \\ \tilde{g}_{41} & \tilde{g}_{42} & \tilde{g}_{43} & \tilde{g}_{44} \\ \tilde{g}_{51} & \tilde{g}_{52} & \tilde{g}_{53} & \tilde{g}_{54} \end{pmatrix} \otimes \begin{pmatrix} \tilde{w}_1 \\ \tilde{w}_2 \\ \tilde{w}_3 \\ \tilde{w}_4 \end{pmatrix} \quad (13)$$

Therefore, total fuzzy grade $\tilde{R}_1$ of alternative A_1 is shown as follows:

$$\tilde{R}_1 = (\tilde{g}_{11} \times \tilde{w}_1) + (\tilde{g}_{12} \times \tilde{w}_2) + (\tilde{g}_{13} \times \tilde{w}_3) + (\tilde{g}_{14} \times \tilde{w}_4) = (19.96, 29.39, 35.34)$$

In the same way, we obtained the total fuzzy grade vector $\tilde{R}$ as follows:

$$\tilde{R} = \begin{pmatrix} \tilde{R}_1 \\ \tilde{R}_2 \\ \tilde{R}_3 \\ \tilde{R}_4 \\ \tilde{R}_5 \end{pmatrix} = \begin{pmatrix} (19.61, 29.39, 35.34) \\ (19.46, 29.00, 35.17) \\ (18.35, 27.91, 34.64) \\ (16.66, 26.29, 33.74) \\ (16.51, 26.38, 33.78) \end{pmatrix} \quad (14)$$

Step 5 : Calculate the ranking order based on the total integral value.

The ranking involves two parts which are the ranking of weight of criteria and the ranking of alternatives. Based on Equations (2.10) and (3.1), the total integral value of weight of criteria is shown in Table 9 for $\beta = 0$, $\beta = 0.5$, $\beta = 1$.

Table 9: The total integral value for each criterion for $\beta = 0$, $\beta = 0.5$, $\beta = 1$

Triangular Fuzzy Numbers	$\beta = 0$	$\beta = 0.5$	$\beta = 1$
$\tilde{w}_1 = (0.623, 0.770, 0.896)$	$R(\tilde{w}_1) = 0.34825$	$R(\tilde{w}_1) = 0.382375$	$R(\tilde{w}_1) = 0.4165$
$\tilde{w}_2 = (0.729, 0.856, 0.919)$	$R(\tilde{w}_2) = 0.39625$	$R(\tilde{w}_2) = 0.4200$	$R(\tilde{w}_2) = 0.44375$
$\tilde{w}_3 = (0.682, 0.826, 0.919)$	$R(\tilde{w}_3) = 0.377$	$R(\tilde{w}_3) = 0.406625$	$R(\tilde{w}_3) = 0.43625$
$\tilde{w}_4 = (0.770, 0.904, 0.956)$	$R(\tilde{w}_4) = 0.4185$	$R(\tilde{w}_4) = 0.44175$	$R(\tilde{w}_4) = 0.465$

Based on Equations (2.10) and (3.4), the total integral value of alternatives is shown in Table 10 for $\beta = 0$, $\beta = 0.5$, $\beta = 1$.

Table 10: The total integral value for each alternative for $\beta = 0$, $\beta = 0.5$, $\beta = 1$

Triangular Fuzzy Numbers	$\beta = 0$	$\beta = 0.5$	$\beta = 1$
$\tilde{R}_1 = (19.61, 29.39, 35.34)$	$R(\tilde{A}_1) = 12.25$	$R(\tilde{A}_1) = 14.22$	$R(\tilde{A}_1) = 16.19$

$\tilde{R}_2=(19.46, 29.00, 35.17)$	$R(\tilde{A}_2)=12.12$	$R(\tilde{A}_2)=14.09$	$R(\tilde{A}_2)=16.05$
$\tilde{R}_3=(18.35, 27.91, 34.64)$	$R(\tilde{A}_3)=11.57$	$R(\tilde{A}_3)=13.61$	$R(\tilde{A}_3)=15.64$
$\tilde{R}_4=(16.66, 26.29, 33.74)$	$R(\tilde{A}_4)=10.74$	$R(\tilde{A}_4)=12.88$	$R(\tilde{A}_4)=15.01$
$\tilde{R}_5=(16.51, 26.38, 33.78)$	$\tilde{A}_5)=10.73$	$R(\tilde{A}_5)=12.89$	$\tilde{A}_5)=15.04$

Step 6: Rank the importance of criteria and performance of alternatives .

From Table 9, for $\beta = 0, \beta = 0.5, \beta = 1$, since $R(\tilde{w}_1) < R(\tilde{w}_3) < R(\tilde{w}_2) < R(\tilde{w}_4)$, thus produce the ranking result as $\tilde{w}_1 < \tilde{w}_3 < \tilde{w}_2 < \tilde{w}_4$, as shown in Table 11.

Table 11: The ranking value for each criterion and ranking results for $\beta = 0, \beta = 0.5, \beta = 1$

Ranking value	Results
$\beta = 0$	$R(\tilde{w}_1) < R(\tilde{w}_3) < R(\tilde{w}_2) < R(\tilde{w}_4)$
$\beta = 0.5$	$R(\tilde{w}_1) < R(\tilde{w}_3) < R(\tilde{w}_2) < R(\tilde{w}_4)$
$\beta = 1$	$R(\tilde{w}_1) < R(\tilde{w}_3) < R(\tilde{w}_2) < R(\tilde{w}_4)$
Ranking results for $\beta = 0, \beta = 0.5, \beta = 1$	$\tilde{w}_1 < \tilde{w}_3 < \tilde{w}_2 < \tilde{w}_4$

Based on Table 10, for $\beta = 0$, since $R(\tilde{A}_4) < R(\tilde{A}_5) < R(\tilde{A}_3) < R(\tilde{A}_2) < R(\tilde{A}_1)$, thus produce the ranking result as $\tilde{A}_4 < \tilde{A}_5 < \tilde{A}_3 < \tilde{A}_2 < \tilde{A}_1$. Meanwhile, for $\beta = 0.5, \beta = 1$, since $R(\tilde{A}_4) < R(\tilde{A}_5) < R(\tilde{A}_3) < R(\tilde{A}_2) < R(\tilde{A}_1)$, thus produce the ranking result for $\beta = 0.5$ and $\beta = 1$ as $\tilde{A}_4 < \tilde{A}_5 < \tilde{A}_3 < \tilde{A}_2 < \tilde{A}_1$ as shown in Table 12.

Table 12: The ranking value for each alternative and ranking results for $\beta = 0, \beta = 0.5, \beta = 1$

Ranking value	Results	Ranking
$\beta = 0$	$R(\tilde{A}_5) < R(\tilde{A}_4) < R(\tilde{A}_3) < R(\tilde{A}_2) < R(\tilde{A}_1)$	$\tilde{A}_5 < \tilde{A}_4 < \tilde{A}_3 < \tilde{A}_2 < \tilde{A}_1$
$\beta = 0.5$	$R(\tilde{A}_4) < R(\tilde{A}_5) < R(\tilde{A}_3) < R(\tilde{A}_2) < R(\tilde{A}_1)$	$\tilde{A}_4 < \tilde{A}_5 < \tilde{A}_3 < \tilde{A}_2 < \tilde{A}_1$
$\beta = 1$	$R(\tilde{A}_4) < R(\tilde{A}_5) < R(\tilde{A}_3) < R(\tilde{A}_2) < R(\tilde{A}_1)$	$\tilde{A}_4 < \tilde{A}_5 < \tilde{A}_3 < \tilde{A}_2 < \tilde{A}_1$

4. Result and Discussion

In this study, criterion X_4 (Functionality) was ranked first for all types of decision makers followed by X_2 (Efficiency), X_3 (Quality), and X_1 (Features). Thus, functionality is the main factor in determining which mathematical applications to choose. The ranking result is consistent with Wang *et al.* (2006) which use the centroid point method as shown in Table 13.

Table 13: The ranking of weight of criterion using centroid point from Wang *et al.* (2006)

Fuzzy numbers	$\bar{x}_0(\tilde{R}_i)$	$\bar{y}_0(\tilde{R}_i)$	R
$\tilde{w}_1 = (0.623, 0.770, 0.896)$	$\bar{x}_0(\tilde{R}_1) = 0.763$	$\bar{y}_0(\tilde{R}_1) = \frac{1}{3}$	$R(\tilde{A}_1) = 0.763$
$\tilde{w}_2 = (0.729, 0.856, 0.919)$	$\bar{x}_0(\tilde{R}_2) = 0.835$	$\bar{y}_0(\tilde{R}_2) = \frac{1}{3}$	$R(\tilde{A}_2) = 0.835$
$\tilde{w}_3 = (0.682, 0.826, 0.919)$	$\bar{x}_0(\tilde{R}_3) = 0.809$	$\bar{y}_0(\tilde{R}_3) = \frac{1}{3}$	$R(\tilde{A}_3) = 0.809$
$\tilde{w}_4 = (0.770, 0.904, 0.956)$	$\bar{x}_0(\tilde{R}_4) = 0.877$	$\bar{y}_0(\tilde{R}_4) = \frac{1}{3}$	$R(\tilde{A}_4) = 0.877$
Ranking value	$R(\tilde{w}_1) < R(\tilde{w}_3) < R(\tilde{w}_2) < R(\tilde{w}_4)$		
Ranking results	$\tilde{w}_1 < \tilde{w}_3 < \tilde{w}_2 < \tilde{w}_4$		

On the other hand, the final ranking for alternatives has slightly different ranking results for $\beta = 0$ and $\beta = 0.5$, and $\beta = 1$. The final ranking result for $\beta = 0$, which represents pessimism is $A_5 < A_4 < A_3 < A_2 < A_1$. Meanwhile, the ranking result for $\beta = 0.5$ and $\beta = 1$, which represent neutral

and optimistic alternatively is $A_4 < A_5 < A_3 < A_2 < A_1$. The ranking result $\beta = 0.5$ and $\beta = 1$ is consistent with the centroid point by Wang *et al.* (2006) as shown in Table 14.

Table 14: The ranking of alternative using centroid point from Wang *et al.* (2006)

Fuzzy numbers	$\bar{x}_0(\tilde{R}_i)$	$\bar{y}_0(\tilde{R}_i)$	R
$\tilde{R}_1=(19.61, 29.39, 35.34)$	$\bar{x}_0(\tilde{R}_1) = 28.11$	$\bar{y}_0(\tilde{R}_1) = \frac{1}{3}$	$R(\tilde{A}_1) = 28.11$
$\tilde{R}_2=(19.46, 29.00, 35.17)$	$\bar{x}_0(\tilde{R}_2) = 27.88$	$\bar{y}_0(\tilde{R}_2) = \frac{1}{3}$	$R(\tilde{A}_2) = 27.88$
$\tilde{R}_3=(18.35, 27.91, 34.64)$	$\bar{x}_0(\tilde{R}_3) = 26.97$	$\bar{y}_0(\tilde{R}_3) = \frac{1}{3}$	$R(\tilde{A}_3) = 26.97$
$\tilde{R}_4=(16.66, 26.29, 33.74)$	$\bar{x}_0(\tilde{R}_4) = 25.70$	$\bar{y}_0(\tilde{R}_4) = \frac{1}{3}$	$R(\tilde{A}_4) = 25.70$
$\tilde{R}_5=(16.51, 26.38, 33.78)$	$\bar{x}_0(\tilde{R}_5) = 25.56$	$\bar{y}_0(\tilde{R}_5) = \frac{1}{3}$	$R(\tilde{A}_5) = 25.56$
Ranking value	$R(\tilde{A}_5) < R(\tilde{A}_4) < R(\tilde{A}_3) < R(\tilde{A}_2) < R(\tilde{A}_1)$		
Ranking results	$\tilde{A}_5 < \tilde{A}_4 < \tilde{A}_3 < \tilde{A}_2 < \tilde{A}_1$		

Based on the results, for neutral and optimistic decision maker Symbolab was ranked the first, followed by Photomath, Mathway, Malmath and Cymath. While for pessimistic decision maker Photomath was ranked the first, followed by Symbolab, Mathway, Malmath and Cymath.

5. Stastistical Analysis

Mathematics mobile applications take advantage of how common mobile devices like smartphones and tablets are to give students exciting and engaging ways to learn mathematics. To measure the engagement of students on the Mathematics mobile applications, it is found that out of 100 respondents, 67% are females and the remaining 33% are males students. About 85% of the respondents are from semester 5, 4% each for semester 1 and 3. While, the remaining 6% and 1% are semester 4 and semester 2 respectively. When they were asked whether they have used any of the mathematics mobile applications, 100% of the respondents stated that they have used this kind of application before.

The criteria used to evaluate mobile learning applications like Symbolab, Photomath, Mathway, Malmath, and Cymath are divided into four main categories: Features (X_1), Efficiency (X_2), Quality (X_3), and Functionality (X_4). Figure 2 specifically compares the mean scores for each application based on three sub-criteria under the Features category: Approachability, Discoverability, and Organisation.

In Figure 2, Symbolab consistently achieved the highest scores across all three sub-criteria compared to the other applications. The lowest mean score for Symbolab was 3.11 (Approachability), and the highest was 3.61 (Discoverability). These signify that in term of approachability, discoverable and whether it is well-organised, Symbolab is within the range of being Fair(F) to Medium Good (MG). Following Symbolab, PhotoMath and Mathway also performed well, though with slightly lower scores. Malmath and Cymath ranked lowest, with only marginal differences in their scores.

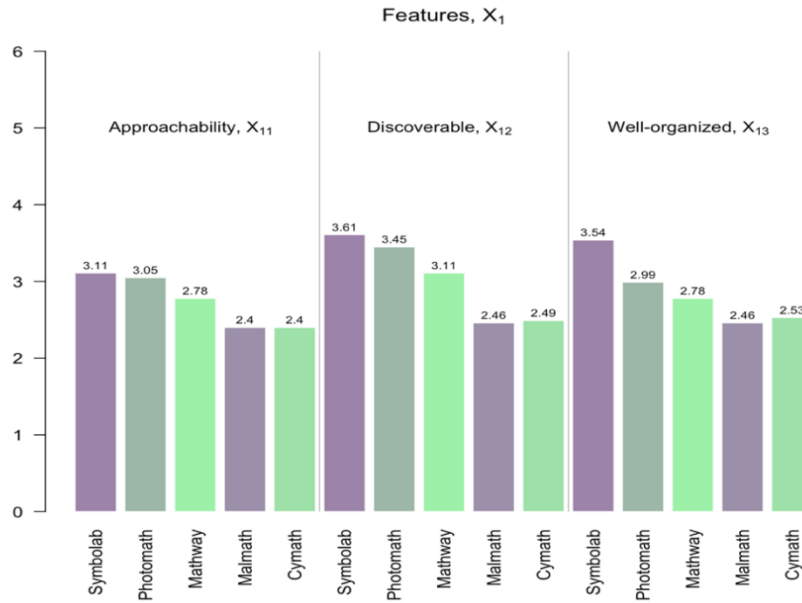


Figure 2: Comparisons of features criteria among alternatives

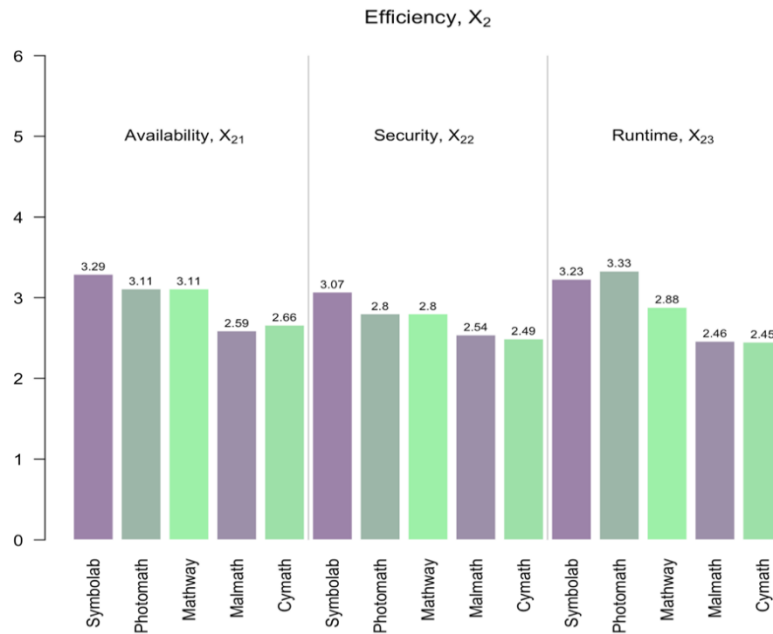


Figure 3: Comparisons of criteria efficiency for each alternatives

Next, Figure 3 specifically compares the mean scores for each application based on three sub-criteria under the Efficiency category: Availability, Security, and Runtime. Based on the bar chart, Symbolab still managed to consistently achieve the highest scores only two sub-criteria compared to the other applications. On average for efficiency, Symbolab managed to get mean scores values between 3.07 to 3.29 for all sub -criteria (Availability, Security, and Runtime). These imply that, in terms of assessing whether the specific application is of high quality, factors such as its effectiveness, error handling, and user-friendliness should be

considered. Symbolab is rated to be within the range of being Fair(F) to Medium Good (MG). This trump all the other applications except for sub-criteria Runtime where Photomath perform slightly better with a margin of only 0.10 under this sub-criterion. Malmath and Cymath maintained ranked lowest, with only negligible differences in their scores.

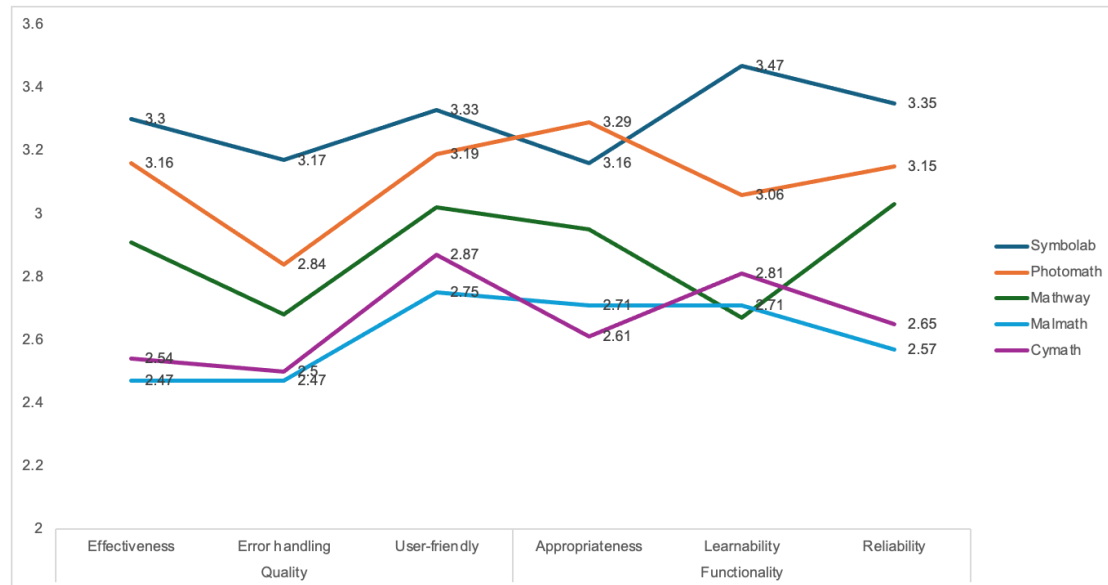


Figure 4: Comparisons of criteria and sub-criteria of Quality and Functionality for each alternative

Figure 4 specifically compares the mean scores for each application based on three sub-criteria under the Quality and Functionality categories. The sub-criteria for Quality are Effectiveness, Error Handling, and User-friendly. The figure shows that, Symbolab still consistently achieves the topmost scores across all three sub-criteria compared to the other applications. Symbolab managed to get values between 3.17 to 3.33 for all sub -criteria. These imply that, in terms of assessing whether the specific application is of high quality, factors such as its effectiveness, error handling, and user-friendliness should be considered. Symbolab is again rated to be within the range of being Fair (F) to Medium Good (MG). This surpasses all the other applications, followed closely by Photomath and Mathway.

Meanwhile, for Functionality sub-criteria which are Appropriateness, Learnability and Reliability. Only for sub-criteria Appropriateness, Photomath manage to surpass Symbolab at 3.29. The Learnability and Reliability both are dominated by Symbolab again rated to be within the range of being Fair(F) to Medium Good (MG). However, for both criteria Malmath and Cymath recorded with only insignificant differences in their scores maintained the lowest rated application as range within Medium Poor (MP) to Fair (F).

To make a clear comparison considering only the main criteria, the radar chart in Figure 5, clearly depict the larger area covered by Symbolab suggesting this application maintaining the mean rating received for all main criteria with larger area covered. The value recorded as in Table 6, where on average for all main criteria, Symbolab have the highest values especially for Features ($X_1 = 3.42$), Efficiency ($X_2 = 3.20$), Quality ($X_3 = 3.27$) and Functionality ($X_4 = 3.33$). The smallest area covered by Cymath where the values for Features ($X_1 = 2.47$), Efficiency ($X_2 = 2.53$), Quality ($X_3 = 2.64$) and Functionality ($X_4 = 2.69$). Based on the linguistics term used for the criteria, when the rate equal to 2 it is Medium Poor (MP), 3 is Fair(F) and 4 is Medium Good (MG). Symbolab is rated to be within the range of being Fair(F) to Medium Good(MG) compared to Cymath within the range of Medium Poor(MP) to Fair(F).

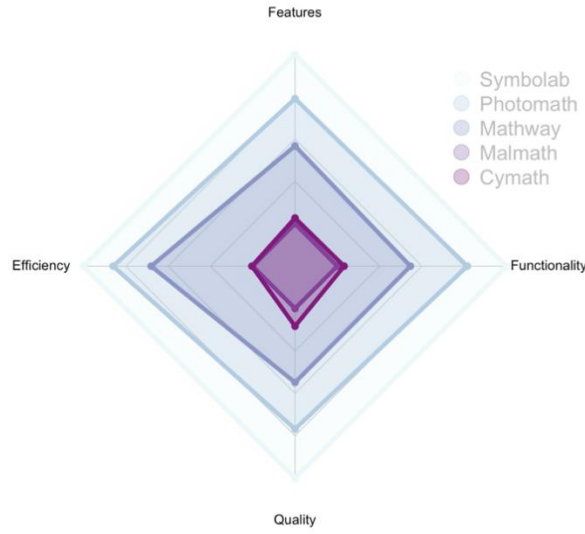


Figure 5. Overall comparisons of main criteria for each alternative

Table 15: Descriptive analysis of mean scores of main criteria

Application	Features	Efficiency	Quality	Functionality
Symbolab	3.42	3.20	3.27	3.33
Photomath	3.16	3.08	3.06	3.17
Mathway	2.89	2.93	2.87	2.95
Malmath	2.44	2.53	2.56	2.66
Cymath	2.47	2.53	2.64	2.69

The results obtained with the statistical analysis, confirming the users' preferences for mobile mathematics mobile applications. The order of preference is Symbolab, followed by Photomath, Mathway, Malmath, and Cymath. Both the fuzzy grade matrix with degree of optimism approach ($\beta = 0.5$, $\beta = 1$) and the fuzzy grade matrix with centroid point indicate that alternative A_1 (Symbolab) is the best choice, followed by alternatives A_2 (Photomath), A_3 (Mathway), A_4 (Malmath), and A_5 (Cymath). This aligns with the findings of the fuzzy approach. The consistency between the Fuzzy Grade Matrix (FGM) ranking and the descriptive statistical mean analysis supports the reliability of the findings. Both methods showed the same preference order, where Symbolab was ranked as the most preferred mathematics mobile application, followed by Photomath, Mathway, Malmath, and Cymath. This similarity shows that the fuzzy evaluation results are consistent with the actual mean scores obtained from students' responses. Since the fuzzy method considers subjective judgement and uncertainty, while the statistical analysis reflects the average preference scores, the agreement between both approaches provides stronger support for the final ranking results. This strengthens the validity of the findings and increases confidence in the overall conclusions.

6. Conclusion

This study used a fuzzy decision-making approach to determine students' preferred mathematics mobile applications. Five popular applications such as Symbolab, Photomath, Mathway, Malmath, and Cymath were evaluated based on four criteria: features, efficiency, quality, and functionality. The Fuzzy Grade Matrix (FGM) with degree of optimism was applied to rank the alternatives while accounting for uncertainty and subjectivity in students'

responses. The results showed that functionality and efficiency were the most important factors influencing students' choices, while features were less significant. Among the applications, Symbolab ranked the highest, followed by Photomath, Mathway, and Malmath, whereas Cymath was the least preferred. The descriptive statistical analysis supported these findings, showing consistent results with only minor variations between the two methods. Compared with previous studies that used fuzzy-based methods independently (e.g., Başaran & El Homsy 2022; Anbarkhan 2023; Al-Gerafi *et al.* 2024), this study uniquely integrates fuzzy analysis with statistical validation on the same dataset. This combination enhances result consistency and provides a more comprehensive interpretation of students' preferences. Overall, the study demonstrates that combining fuzzy and statistical approaches offers a clearer understanding of students' choices in mathematics mobile applications. Future research could apply Intuitionistic Fuzzy Decision-Making (IFDM) which considers both membership and non-membership functions, to capture uncertainty and hesitation more effectively. It is also recommended to include a larger and more diverse group of respondents to enhance the reliability, generalisation, and practical relevance of the results.

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