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A Fuzzy MCDM Rating Method for Supply Chain Mobile Apps

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Abstract

Supply chain management mobile applications have been beneficial in managing real-time orders and tracking of goods, inventory control, and cost optimization. However, the exponential growth of supply chain mobile applications has made it difficult for users to select the optimal application to suit their supply chain needs. Existing mobile app rating tools such as the Mobile App Rating Scale (MARS) and Feature-based Application Rating Method were developed with a focus in the health sector and are also not designed to capture the subjective nature of responses for rating supply chain mobile apps. This study therefore developed the Fuzzy Mobile App Rating Scale (FMARS) for rating supply chain mobile apps. To accomplish this, the study first established the major factors deemed important to the performance of supply chain mobile applications and computed their relative importance weights using the fuzzy Pairwise Comparison method. The factors and their related importance weights were employed in a fuzzy TOPSIS framework to rank selected supply chain mobile apps from Apple Store and Google Play Store based on an established inclusion criteria. Findings suggest that the developed FMARS is remarkably practical for the ranking and selection of mobile apps, especially when rating data solicited is imprecise.

Keywords
Supply chain, mobile apps, importance weights, fuzzy MCDM

1. Introduction
The rapid growth of mobile phones worldwide makes mobile application one of the fastest-growing technologies (Raeesi et al., 2022). Mobile applications consist of software that run on a mobile device to perform certain tasks for the user. (Nochkin, 2013). Mobile apps presently perform more advanced functions other than the mere calling, messaging, audio and video and there has been so much progress that it now supports supply chain management. Supply chains are essential networks that enable the production and distribution of goods globally (Büyüközkan and Göçer, 2022). As supply chains grow more complex with globalization, mobile technology has emerged as an invaluable tool for managing logistics and enabling supply chain visibility (Sufiyan et al., 2019). The supply chain management mobile software market is projected to reach $15.5 billion by 2027, indicating the rising importance of mobility in streamlining supply chain operations (MnM, 2022). Implementing mobile applications can provide various advantages like real-time tracking, coordinating logistics, reducing costs and risks, and improving collaboration across supply chain stakeholders (Verma and Singh, 2022). However, challenges still exist regarding effective evaluation and selection of the most suitable mobile applications for supply chain needs.

Supply Chain Management Mobile Apps (SCMMA) refers to the use of mobile apps and devices to facilitate supply chain operations, which helps businesses in cost reductions, supply chain responsiveness, and competitive advantage (Nysveen et al., 2015). Examples of these apps are Logistimo Plus which enables users to manage supply chain in rural emerging markets, Scandit which promotes inventory process with a barcode scanning technology, Servicemax which provides field productivity and many more. SCMMA has several benefits such as enabling firms to render services to customers regardless of their location, ensuring efficient flow and exchange of supply chain activities from the commencement of a product, design, production, sales, customer service to the end of a product's lifespan. SCMMA also enable real-time shipment tracking, field workforce coordination, inventory analytics, and overall supply chain visibility (Verma and Singh, 2022). However, with over 16,000 mobility solutions on the market (Statista, 2021), optimal app selection is challenging. Firms struggle to evaluate options against important criteria like security, costs, ease of use, and customization capabilities amidst vague standards between competing vendors (Wamba and Chhatfield, 2019). Yet poor app choices can negatively impact productivity, resilience, and adaptation when disruptions hit (Ivanov, 2021; Ivanov et al., 2019). Even though experimental trials are still the best approach to assess the effectiveness of these applications, they are not always feasible in situations where the number of apps is continually increasing, and their functionalities change over time.

The rating of SCMMA is crucial as mobile technology provides real time and on-demand response of which the related decisions are irreversible and affect multiple functions through 'knock-on' supply chain effects, and cause customer dissatisfaction (Nysveen et al., 2015). Thus, it is worth developing a reliable rating instrument to help select SCMMAs that meet established supply chain performance criteria.

Thus, there is an urgent need for a model for evaluating mobile supply chain applications, filling a concerning knowledge gap (Büyüközkan and Göçer, 2018; Sabri Laghzaoui et al., 2020).

Second, the rise of studies evaluating mobile applications using one-fit all list of quality criteria raises questions about the applicability in certain sectors. For example, the criteria developed by Stoyanov et al. (2015) namely functionality, information, engagement, aesthetics in their popular Mobile App Rating Scale (MARS) originally developed for healthcare mobile apps, though useful for general assessments of mobile apps, does not capture the peculiar criteria for assessing the quality of mobile apps in the supply chain management area. This study surveyed experts to determine a comprehensive set of criteria from costs to customization and functionality capabilities most valuable to industry stakeholders and vital for driving operational excellence in supply chain management.

Third, mobile apps are emerging as the best solution for businesses that are looking to improve the quality of their supply chain. However, it has become challenging for customers, organizations, and researchers to quickly find and analyze good quality applications due to the rapid production of smartphone apps (Cummings et al., 2015). There is little information accessible on the rating of apps, and app reviews by their very nature are subjective and could originate from dubious sources. This can be very problematic in the case of supply chain management, as sub-standard supply chain management mobile apps could lead to lost revenues, customer dissatisfaction, missed production schedules and excessive inventory investment.

Lastly, several studies have evaluated the performance of mobile applications, yet few have used the fuzzy approach for situations when the responses are subjective. One of these is the multi-criteria decision-making problem on ranking selected mobile applications for mathematics using fuzzy scale weights with ELECTRE I (Elimination and Choice Expressing Reality) (Seren and Oluwatobi, 2018). Due to uncertainties which are common in supply chains, the responses to rating questions on SCMMA tend to be subjective and therefore should be analyzed using fuzzy approach. The fuzzy methodology is designed to capture the subjective opinions of evaluators and has been shown to yield better results than non-fuzzy approaches in such situations (Dweiri and Al-Oqla, 2006; Raut et al., 2021). Given the many uncertainties in supply chains and therefore the subjective nature of responses, this research therefore seeks to develop a fuzzy mobile application rating scale specifically for rating supply chain mobile apps. To the best of our knowledge, no study has evaluated mobile applications for supply chain management using fuzzy logic approach. Therefore, the purpose of this study is to investigate and document the most important factors to consider when evaluating supply chain mobile apps, and using these factors assess and rank the quality of supply chain management mobile applications existing in the market.

1.1 Objectives

The objective of this research is therefore to develop a mobile app rating technique that fits the peculiar issues in supply chain management including uncertainties in supply chains. Specifically, the research aims to (1) establish the major criteria for determining the quality of supply chain mobile apps and their relative importance, (2) develop a fuzzy version of the MARS for supply chain management for the cases where some of the criteria seems to be subjective, and (3) apply the developed fuzzy MARS technique for the selection of the best supply chain mobile application.

2. Literature Review

2.1 Supply Chain Apps

Supply chain apps refer to software applications designed to manage and optimize supply chain operations across suppliers, manufacturers, distributors, retailers and end consumers (Barreto, Amaral, and Pereira, 2017). The Supply Chain Management Review (SCMR) defines supply chain app as an application that has supply chain execution capabilities spanning production, distribution, transportation, and analytics (SCMR, 2018; Gartner, 2021). Secondly, Supply chain apps are seen as performance and growth engines for leveraging disruptive technologies to transform people, processes, data, and analytics across organizations (Barreto, Amaral, and Pereira, 2017; (Li et al., 2021).

Fundamentally, supply chain apps enable information flows and coordination between suppliers, manufacturers, transporters, warehouse stores and end-customers that constitute modern distribution networks. By tracking inventory statuses, delivery mechanisms, locations and transit points in real-time, they provide visibility necessary for efficient decision-making when fulfilling demand (Barreto et al., 2017).

Four archetypes are commonly observed - procurement apps automate purchasing workflows, manufacturing apps assist production monitoring and control, logistics apps focus on shipment workflows while analytics apps synthesize datasets to uncover optimization opportunities (Barreto et al., 2017).

With expanding solution maturity, contemporary tools incorporate AI/ML-driven forecasting, IoT and blockchain integration for traceability, cloud-based control towers with digital twin representations, control charts and advanced process mining capabilities like root cause analyses when disruptions occur (Barreto et al., 2017). Consumer-centric functionalities like order tracking with embedded maps, shipment notifications, dynamic ETAs, returns/refunds facilitation and inventory lookups are also embedded for responsiveness (Li et al., 2021).

As supply uncertainty, global customer bases and technology disruptions alter traditional planning assumptions, apps promote agility, continuity and resilience (Li et al., 2021). Real-time data replaces latent indicators while simulations and what-if analysis aid contingency planning for external volatility (Gartner, 2021). Core value propositions thus include consistency, reduced costs through digitization, improved customer service and decision augmentations (Barreto et al., 2017; Li et al., 2021).

Supply chain management (SCM) mobile apps allow companies to monitor and manage complex global production and distribution operations efficiently via smartphones and tablets - providing real-time visibility into inventory levels, logistics, and orders as well as analytical capabilities to enable data-driven decisions (Michaels, 2017).
Adoption of SCM apps is surging driven by mobility demands, real-time data needs and emerging technologies advancing the sophistication of solutions (Abrams, 2019; Michaels, 2017) - spending on supply chain mobile apps worldwide is estimated to grow at 11% annually to exceed $15 billion by 2026 (Johnson, 2018).

2.2 Mobile App Rating Scale (MARS)

Stoyanov et al. (2015) developed the Mobile App Rating Scale (MARS) as a tool for evaluating the quality of mobile health apps. Since then, MARS has been used to rate mobile apps across diverse domains including education, business, and general consumer applications. MARS provides a framework for classifying and assessing apps based on four quality dimensions - engagement, functionality, aesthetics, and information quality. The engagement dimension covers entertainment, interest, customization, interactivity, and target group suitability factors, whereas functionality covers performance, ease of use, navigation and gestural design. Aesthetics looks at layout, graphics and visual appeal whereas information quality looks at accuracy, goals, quality, quantity, visual appeal and credibility of the app information.

In general, the mean score of the ratings from the four dimensions is used to judge the overall app quality of the evaluated mobile apps. MARS has been found to have high internal consistency and good inter-rater reliability in studies across contexts like mental health and wellbeing, chronic disease management, fitness, and healthcare professional training (Stoyanov et al, 2015). The reliability and flexibility of MARS has contributed to its extensive adoption as a standard for app quality evaluation.

However, despite the popularity of MARS, using it in a supply chain context requires developing dedicated subscales with tailored criteria that capture the nuances as related to supply chain management. Supply chains have complex operational and decision-making requirements related to production monitoring, inventory control, shipment tracking, coordinating logistics, and enabling end-to-end visibility. This clearly calls for a new set of criteria for assessing supply chain mobile apps that goes beyond the original MARS criteria.

2.3 Fuzzy MCDM

A fuzzy MCDM (multi-criteria decision-making) model is a decision-making model that allows the incorporation of fuzzy logic and fuzzy sets to handle subjective, uncertain, and imprecision evaluations in the decision-making process (Saghafian and Hejazi, 2005). Specifically, the imprecise nature of human judgments is captured with fuzzy numbers (Kahraman, Onar, and Oztaysi, 2015). The term fuzziness may also refer to stochasticity, vagueness, and rough approximations within a decision system (Dou, Zhu, and Sarkis, 2018; Jana, Roy, and Majumder, 2017). At its core, a fuzzy MCDM approach allows the inclusion of fuzzy information while evaluating multiple criteria in a decision-making problem (Abdel-Basset, Mohamed, and Chang, 2018).

Fuzzy MCDM generally employs fuzzy set theory in MCDM methods to model imprecise information, incomplete preferences, and partial truths (Dou, Zhu, and Sarkis, 2018; Kahraman et al., 2015). The use of fuzzy set theory permits the mathematical representation of ambiguity, rather than ignoring or simplifying it, thereby leading to results that are more concrete and realistic (Jana et al., 2021; Kahraman, 2018). As an example, the use of a triangular fuzzy number would use three numbers, say (7,8,9) instead of a single number say the number 8, to represent a decision maker's rating of say '*very long*' and thus capture any imprecision in the mind of the decision maker.

Fuzzy set theory can also be used in determining weights of criteria, so that any imprecision in the ratings provided by experts is also captured. In this case, the fuzzy weights get defuzzified if a crisp value is required (Dou et al., 2018; Kahraman et al., 2015). There is a fuzzy version for almost all MCDM techniques. These include fuzzy AHP for hierarchical criteria modeling, fuzzy TOPSIS for ranking preferences, fuzzy VIKOR, fuzzy PROMETHEE, fuzzy ELECTRE, and fuzzy DEMATEL. Given that issues concerning supply chain tends to exhibit uncertainty or imprecision primarily due to the bullwhip effect (Alvarado-Vargas, and Kelley, 2020), it is imperative that supply chain mobile apps are evaluated using the fuzzy approach. Therefore, this study builds upon MARS and proposes the Fuzzy Mobile Application Rating Scale (FMARS) for the evaluation of supply chain mobile apps better capture the imprecision in both the responses from experts in the determination of criteria weights, and in the responses obtained when evaluating alternative supply chain mobile apps.

3. Methods

The methodology employed in this work can be classified into three parts. The first part concerns the approach for establishing the relevant criteria for evaluating supply chain mobile apps. The second part focusses on the determination of the relative importance weight of the criteria whereas the third part uses the information from the first two parts to evaluate and rank selected supply chain mobile apps.

3.1 Identification of Relevant Criteria for Evaluating SCMMAs

Supply chain management mobile applications (SCMMAs) aim to provide real-time visibility and optimized decision-making related to production, inventory, logistics, and coordination processes through easy-to-use mobile access (Khan et al, 2022). Therefore, an extensive review of the literature was conducted to determine criteria vital for SCMMA success in relation to these drivers. Factors centered around information/analytics, system quality, and service interaction quality were deemed most salient (Sabouhi et al., 2021). Additionally, research highlight the growing need for scalability, integration, collaboration, and accessibility critical for SCMMAs to handle global supply chain complexity and disruption risks (Baldwin, and Freeman, 2022). The final criteria identified based on the literature review are summarized in Table 1, along with the sources.

Table 1. Selected criteria relevant for evaluating SCMMAs

Criteria	**Description**	**Sources**
Fascinating	App is exciting to use and has engaging supply chain management content	Sabouhi et al., 2021; Pan et al., (2013); Stoyanov et al., (2015)
Customization	App provides a means for users to modify or upgrade features to meet their specific needs	Sabouhi et al., 2021; Pan et al., (2013); ; Stoyanov et al., (2015)
Interactivity	App enables user input, gives feedback, and includes prompts (reminders, sharing options, and notifications)	Sabouhi et al., 2021; Stoyanov et al., (2015)
Target Group	App's content is suitable for the intended audience	Sabouhi et al., 2021; Stoyanov et al., (2015)
Performance	App's components and features operate quickly and precisely	Pan et al., (2013); Stoyanov et al., (2015),
Ease of Use	Easy to access the app's menu and navigate through	Pan et al., (2013); Stoyanov et al., (2015),
Gestural Design	There's consistency and understanding in interactions between app's components and screens	Pan et al., (2013); Stoyanov et al., (2015),
Maintainability	App is always accessible and easy to maintain	Pan et al., (2013); Stoyanov et al., (2015),
Layout	Buttons, icons and content on the screen are sized appropriately and can be magnified if necessary	Stoyanov et al., (2015)
Graphics	App has detailed graphics used for buttons, icons, and SCM content	Stoyanov et al., (2015),
Visual Appeal	App has intriguing features (eg. real-time updates, portability, precision monitoring, accurate delivery)	Stoyanov et al., (2015)
Quality of Information	App's SCM content is accurate and pertinent to its purpose and subject	Stoyanov et al., (2015)
Quantity of Information	App's domain has broad coverage and adequate information	Stoyanov et al., (2015)
Visual Information	App has charts, graphs, and other visual representations of SCM concepts for faster decision making.	Stoyanov et al., (2015)
Credibility	app is authentic (specified in the app store description or within the app itself).	Stoyanov et al., (2015)
Authentication	app has a strong multi-factor authentication to prevent unauthorized access and password guessing attacks.	Stoyanov et al., (2015)
Encryption	Communications between the app and other mobile apps and app servers are encrypted	Stoyanov et al., (2015)
Platform Security	app's mobile workspace is secured and prevents data leaks (Prevention of malware from accessing corporate apps and stops users from unauthorized copying, saving or distributing sensitive data)	Stoyanov et al., (2015)

The 18 selected criteria were further divided into five groups, namely Engagement, Functionality, Aesthetics, Information, and Security as shown in Table 2 below.

Table 2. Selected criteria relevant for evaluating SCMMAs

Main Criteria	Sub Criteria
ENGAGEMENT	Fascinating
	Customization
	Interactivity
	Target Group
FUNCTIONALITY	Performance
	Ease of Use
	Gestural Design
	Maintainability
AESTHETICS	Layout
	Graphics
	Visual Appeal
INFORMATION	Quality of Information
	Quantity of Information
	Visual Information
	Credibility
SECURITY	Authentication
	Encryption
	Platform Security

3.2 Expert Evaluation of Criteria Importance Weights

A panel of six leading supply chain experts across academia and industry evaluated the relative importance of the identified criteria for SCMMA selection. The experts had an average of over 10 years of experience managing global supply chain operations, technologies, and strategies. A questionnaire containing a pairwise comparison set up for the selected criteria was administered, enabling experts to rate multiple combinations of criteria based on importance. The Fuzzy AHP tool was used to analyze survey responses and derive weights reflecting the overall importance placed on each criterion by the expert panel. In all, experts were to rate the 18 selected criteria based on the nine (9) linguistic variables listed in the first column of Table 3. The corresponding numeric ratings of the linguistic variables are shown in columns 2 and 3 depending on whether a compared criterion is better or worse to the criterion it is compared with. Table 4 shows an example response from one of the experts on the pairwise comparison of the five main criteria. As seen in Table 4, unlike other techniques, a pairwise comparison technique ensures that a decision maker compares each criterion with every other criterion. The experts were also asked to rate the sub-criteria under each main criterion using pairwise comparison set up similar to that shown in Table 4.

Table 3. The 9-point linguistic scale for rating the SCMMA criteria

	TFN of numerical ratings between 1 and 9		**TFN of the reciprocal of ratings between 1 and 9**	
Scale (Linguistic Variable)	**Rating**	**TFN**	**Rating**	**TFN**
Equal importance	1	1,1,1	1	1,1,1
Somewhat between Equal and Moderate	2	1,2,3	1/2	1/3,1/2,1
Moderately more important than	3	2,3,4	1/3	1/4,1/3,1/2
Somewhat between Moderate and Strong	4	3,4,5	1/4	1/5,1/4,1/3
Strongly more important than	5	4,5,6	1/5	1/6,1/5,1/4
Somewhat between Strong and Very Strong	6	5,6,7	1/6	1/7,1/6,1/5
Very strongly important than	7	6,7,8	1/7	1/8, 1/7,1/6
Somewhat between Very strong and Absolute	8	7,8,9	1/8	1/9,1/8,1/7
Absolutely more important than	9	8,9,10	1/9	1/10,1/9,1/8

Table 4. Pairwise comparison rating of criteria using the 9-point scale by a decision maker.

	C1 (Engagement)	C2 (Functionality)	C3 (Aesthetics)	C4 (Information)	C5 (Security)
C1 (Engagement)	1	1/9	2	1/5	1/9
C2 (Functionality)	9	1	7	1	1
C3 (Aesthetics)	1/2	1/7	1	1/5	1/9
C4 (Information)	5	1	5	1	1
C5 (Security)	9	1	9	1	1

3.3 Criteria weight determination using Fuzzy AHP

The data collected through the pairwise comparison technique was evaluated to establish the importance weights of the selected criteria using fuzzy AHP. The pairwise comparison responses from the experts were first aggregated using the geometric mean method, following which they were normalized. Note that the resulting weights from the fuzzy AHP method were in fuzzy form. Fuzziness was achieved using Triangular Fuzzy Numbers (TFNs) where for two TFNs $\tilde{A}_1 = (L_1, M_1, U_1)$ and $\tilde{A}_2 = (L_2, M_2, U_2)$, L and U are the lower and upper bounds, and M is the modal value. The tilde symbol represents fuzziness. In addition, the following five equations holds for the two TFNs:

Eqn (1): Addition of TFN: $\tilde{A}_1 + \tilde{A}_2 = (L_1, M_1, U_1) + (L_2, M_2, U_2) = (L_1 + L_2, M_1 + M_2, U_1 + U_2)$

Eqn (2): Subtraction of TFN: $\tilde{A}_1 - \tilde{A}_2 = (L_1, M_1, U_1) - (L_2, M_2, U_2) = (L_1 - L_2, M_1 - M_2, U_1 - U_2)$

Eqn (3): Multiplication of TFN: $\tilde{A}_1 \times \tilde{A}_2 = (L_1, M_1, U_1) \times (L_2, M_2, U_2) = (L_1L_2, M_1M_2, U_1U_2)$

Eqn (4):. Division of TFN: $\tilde{A}_1 \oslash \tilde{A}_2 = (L_1, M_1, U_1) \oslash (L_2, M_2, U_2) = (L_1/U_2, M_1/M_2, U_1/L_2)$

Eqn (5):. Reciprocal of TFN: $\tilde{A}_1^{(-1)} = (L_1, M_1, U_1) = (1/U_1, 1/M_1, 1/L_1)$

For Eqn (3), Eqn (4), and Eqn (5) to hold, we must have the lower, upper, and modal values in both TFNs to be positive. The resulting fuzzy weights from the fuzzy AHP method were de-fuzzified using the Best Non-fuzzy Performance (BNP) approach.

3.4 Mobile app selection and ranking procedure

A systematic search of the Apple store and Android play store was conducted on December 1, 2023 to December 15, 2023. This resulted in an in-depth list of supply chain management apps. In all, the search resulted in 244 apps from the Android app store and 55 apps from the Apple store. The following search terms were used, "Supply" or "Supply Chain" or "Supply Chain Management". The inclusion criteria for the initial selected Apps to be considered to be part of the apps for evaluation were that (1) the app should be in English language, (2) app rating should be greater than 4, (3) app should be free of charge, app should have been downloaded more than 1000 times, and app should be under the productivity, business, or shopping category. The category inclusion criteria were based on scrutiny of the titles and types of apps present in those categories. Finally, 6 mobile apps were collected to be evaluated (Figure 1).

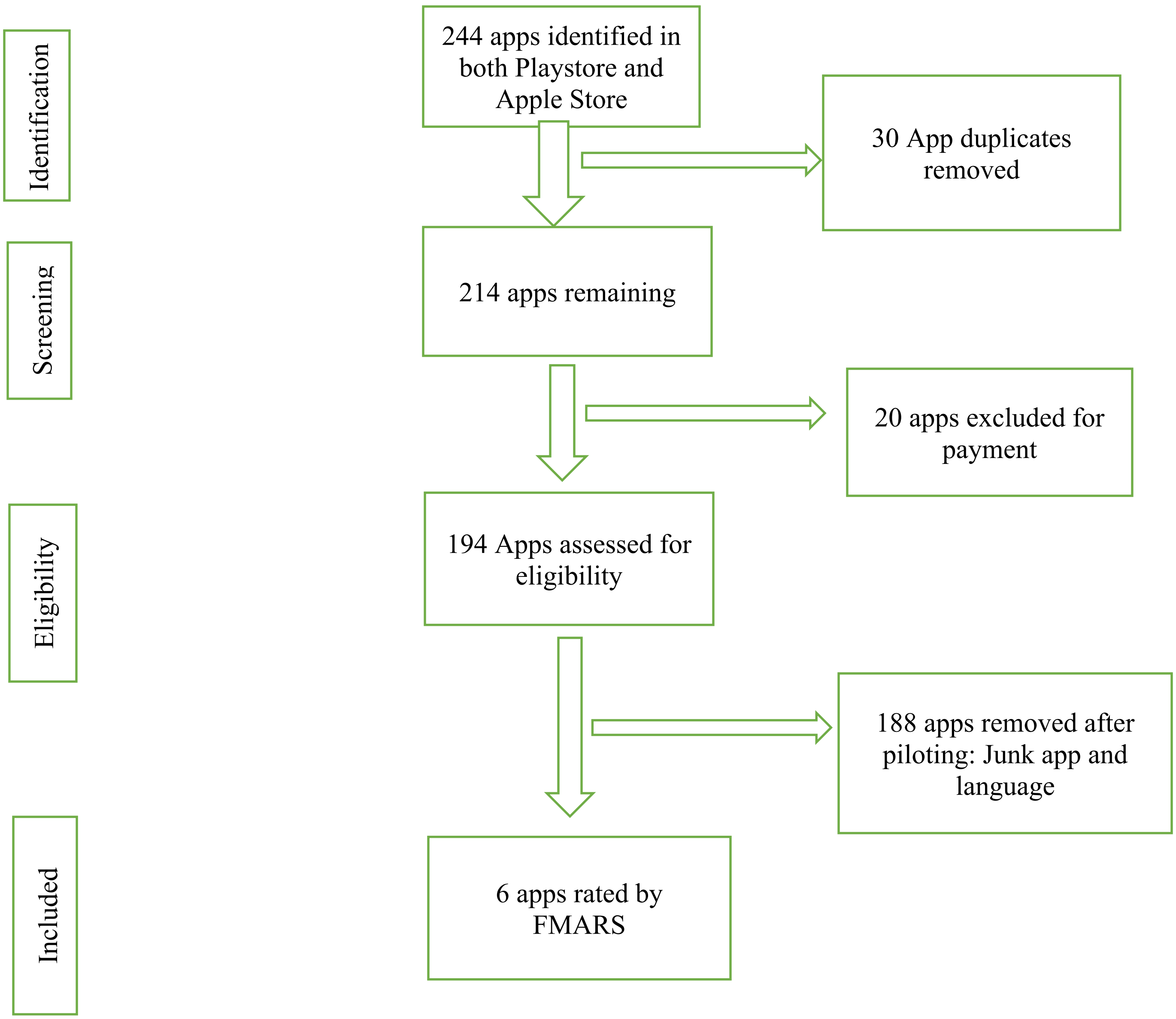

Figure 1. Flowchart of the process utilized to identify apps for piloting the Fuzzy Mobile App Rating Scale (FMARS).

3.4 Ranking of SCMMAs with Fuzzy TOPSIS

Fuzzy TOPSIS was used in the study as the multi-criteria decision analysis technique to evaluate and rank alternative SCMMAs. For more on TOPSIS, we refer the reader to Çelikbilek, and Tüysüz, (2020) and Afful-Dadzie et al (2016). Like the procedure for determining criteria weights, the fuzzy TOPSIS method also makes use of TFNs. In addition, responses from evaluators are also normalized and further weighted to arrive at the so-called separation measures based on which the closeness coefficient is computed for rank determination. In all, the performance of a group of supply chain mobile apps is determined by arranging the relative closeness in a descending order, where the app with the best performance is the one with the largest closeness coefficient.

4. Results and Discussion

4.1 Criteria Weights

The aggregated fuzzy ratings with triangular fuzzy numbers for the five main criteria based on the Geometric Mean method is shown in Table 5. The values in Table 5 were then taken through the fuzzy AHP process resulting in the fuzzy weights as shown in Table 6. The fuzzy weights were further de-fuzzified to obtain single numbers using the Best Non-fuzzy Performance (BNP) method as shown in column three of Table 6. Column four of Table 6 gives the ranking of the five main criteria, implying that of the five criteria, *Functionality* is seen by the experts as the most important, followed by *Security*, then *Engagement* and *Information* in a tie. The criterion *Aesthetic* is seen as the least important among the five criteria.

Table 5. Results of the aggregation of the fuzzy number ratings of criteria of all Decision Makers.

	C1 (Engagement)	C2 (Functionality)	C3 (Aesthetics)	C4 (Information)	C5 (Security)
C1 (Engagement)	1.00, 1.00, 1.00	0.79, 0.83, 0.86	1.48, 2.03, 2.49	0.76, 1.03, 1.23	0.56, 0.82, 1.01
C2 (Functionality)	1.26, 1.20, 1.17	1.00, 1.00, 1.00	1.91, 2.45, 2.90	1.26, 1.62, 1.91	0.86, 1.26, 1.58
C3 (Aesthetics)	0.67, 0.49, 0.40	0.52, 0.41, 0.34	1.00, 1.00, 1.00	0.66, 0.75, 0.80	0.51, 0.62, 0.68
C4 (Information)	1.31, 0.97, 0.81	0.79, 0.62, 0.52	1.51, 1.33, 1.25	1.00, 1.00, 1.00	1.09, 1.44, 1.73
C5 (Security)	1.78, 1.22, 0.99	1.17, 0.79, 0.63	1.98, 1.62, 1.46	0.91, 0.69, 0.58	1.00, 1.00, 1.00

Table 6. Calculated fuzzy weights for the main 5 criteria

Criteria	**Fuzzy weights**	**De-Fuzzified weights**	**Rank**
Engagement	0.17, 0.21, 0.24	0.2	3
Functionality	0.23, 0.28, 0.31	0.27	1
Aesthetic	0.12, 0.12, 0.12	0.12	5
Information	0.21, 0.20, 0.19	0.20	3
Security	0.25, 0.20, 0.17	0.21	2

Similar fuzzy AHP runs were conducted among the sub-criteria for each main criterion. Table 7 shows the results of the importance weights for the sub-criteria and the main criteria. In all, Customization was ranked most important under the main criterion of *Engagement*, followed by Interactivity, Target Group, then Fascinating. For the main criterion of *Functionality*, Performance was judged by the experts as the most important, followed by Maintainability, then Ease of Use, then Gestural Design in that order. For the main criterion of *Aesthetic*, Graphics was seen as the most important, followed by Layout, then Visual Appeal. Likewise, for the main criterion *Information*, Quantity of Information was ranked the most important, followed by Visual Information, then Credibility, then Quality of Information. Lastly for the main criterion *Security*, Encryption was seen to be the most important, followed by Authentication, then Platform Security.

Table 7. Importance weights and ranking of the main criteria and related sub-criteria

CRITERIA	Weight of criteria	Rank of criteria	Sub-criteria	Local weights of sub-criteria	Rank of sub-criteria	Global weights of criteria
ENGAGEMENT	0.20	3	Fascinating	0.22	4	0.046
			Customization	0.29	1	0.059
			Interactivity	0.25	2	0.051
			Target Group	0.23	3	0.047
FUNCTIONALITY	0.27	1	Performance	0.44	1	0.120
			Ease of Use	0.19	3	0.052
			Gestural Design	0.17	4	0.046
			Maintainability	0.20	2	0.054
AESTHETICS	0.12	5	Layout	0.35	2	0.042
			Graphics	0.36	1	0.044
			Visual Appeal	0.28	3	0.034
INFORMATION	0.20	3	Quality of Information	0.21	4	0.042
			Quantity of Information	0.33	1	0.067
			Visual Information	0.23	2	0.047
			Credibility	0.22	3	0.045
SECURITY	0.21	2	Authentication	0.33	2	0.069
			Encryption	0.35	1	0.073
			Platform Security	0.31	3	0.064

4.2 Ranking SCMMAs with Fuzzy TOPSIS

The performance of the six supply chain management mobile apps arrived at after the inclusion-exclusion criterion in Figure 1 were then evaluated based on the criteria from Table 7 and the corresponding importance weights. To do this, a 5-point rating scale shown in Table 8 was designed and given to 40 evaluators to use to rate the six selected apps based on the criteria from Table 7. The responses from the evaluators were then evaluated using the Fuzzy Topsis method. Table 9 gives the result from the fuzzy TOPSIS method including the distance from the positive and negative ideal solutions, and the related closeness coefficients. The closeness coefficients result in Table 9 implies that based on the 18 criteria from Table 7, and the ratings provided the evaluators, the supply chain mobile app by name *Store Manager* was found to have the best performance, followed by *Zoho Inventory*, *Stock Control Inventory*, *Stock and Inventory*, *Price Scanner*, and *Stock Manager* in the order of importance.

Table 8. The 5-point linguistic scale for rating the SCMMA alternatives.

Linguistic variables	Numerical Rating	Triangular Fuzzy Number
Strongly Disagree	1	1,1,1
Disagree	2	1,2,3
Neutral	3	2,3,4
Agree	4	3,4,5
Strongly Agree	5	4,5,6

Table 9. Results for the relative closeness to the ideal solution and ranking order of the SCMMAs. The D+ is the distance to the positive ideal solution whereas D- is the distance to the negative ideal solution. CCi gives the closeness coefficient for the competing supply chain management mobile apps.

SCMMA	D+	D-	CCi	Rank
Price Scanner	17.49	0.61	0.03	**5**
Storage Manager	17.33	0.75	0.04	**1**
Stock Control and Inventory	17.39	0.70	0.04	**3**
Stock and Inventory	17.43	0.67	0.04	**4**
Stock Manager	17.50	0.59	0.03	**6**
Zoho Inventory	17.38	0.71	0.04	**2**

5. Conclusion

This study presented a fuzzy version of the Mobile Application Rating Scale (MARS) for ranking supply chain mobile apps which have seen considerable growth in recent times. However, to be able to undertake such rankings required the establishment of the relevant criteria based on which competing supply chain mobile apps could be rated on. Upon an extensive literature search and building upon the criteria of MARS as proposed by Stuyanov et al (2017), five main criteria, namely Engagement, Functionality, Aesthetics, Information, and Security were agreed on by experts to be the most important. The sub-criteria under each of the main criteria were also established. The relative importance weights of the main and the sub-criteria were then determined using the fuzzy AHP method resulting in Functionality seen as the most important of the five main criteria, followed by Security, then Information and Engagement in a tie, and lastly Aesthetics as the least important among the five criteria. Similar rankings were done for all the sub-criteria of the main criteria.

The established criteria and the importance weights were employed in a fuzzy TOPSIS method to evaluate the performance of six supply chain management mobile apps selected from Apple Store and Google Play Store resulting in the app Store Manager judged as the one with the best overall performance.

The developed fuzzy MARS method by this paper is not only practical but also easy to use as it is built on well-established techniques of AHP and TOPSIS.

One of the most important contributions of this study is the establishment of the relevant criteria for evaluating supply chain mobile apps. As stated, these were arrived at after an extensive literature search and input from supply chain management experts. It must be acknowledged that the number of experts who ranked the criteria could have been increased and likewise the medium of selection of the supply chain mobile apps for ranking could have also been expanded, suggesting that it is likely that the importance weights and therefore the ranking of the criteria and the competing supply chain mobile apps could change.

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