An Analytic Hierarchy Process Model for Evaluation of Mobile Health Applications (Usability Approach)

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ABSTRACT

Assessing the usability of mHealth apps is still a herculean task among software usability researchers/engineers as evaluating the usability attributes of these apps require substantial efforts from a wide range of knowledge domains and prospective users. Most usability models possess numerous attributes that can be adequately used to assess these apps but current usability techniques cannot effectively rank numerous qualitative and quantitative usability attributes simultaneously. Hence, the main objective of this work is to rank and prioritize the usability attributes embedded in a model for mobile app evaluation purposes. The model was designed hierarchically based on People at the Center of Mobile Application Development (PACMAD) MODEL and the Integrated Measurement Model (IMM). Attributes considered include efficiency, effectiveness, satisfaction, learnability, operability, user interface aesthetics and universality. They were ranked using their respective priority weights based on the Analytic Hierarchy Process (AHP). Pairwise comparison matrix was formulated based on decision makers' judgements that were aggregated and normalized. Consistency of decision makers' judgements was obtained using Saaty's Eigen value and Eigen vector approach as a result of their simplicity and accuracy. Results of evaluation showed that efficiency and effectiveness had the highest priorities with 30% and 27% while satisfaction and user interface aesthetics had the lowest ranks with 6% and 5% respectively. Overall AHP group consensus results was 68%. In conclusion, it was established that the mathematical technique used is a powerful yet simple tool that has the ability to evaluate both the quantitative and qualitative usability attributes simultaneously. The work presented the assessment of a unified framework that combined the judgements from multiple levels of mHealth apps usability evaluation process. It is recommended that further studies extend the usability model used by increasing the number of usability attributes and for the evaluation to be done using other Multi-criteria Decision Making (MCDM) approaches and for the results obtained to be compared so as to be able to determine the differences or relationships between other MCDM techniques on usability models.

Keywords: **Analytic Hierarchy Process, Mobile health applications, Multi-criteria decision making, Usability models.**

1.0 INTRODUCTION

[16] identified usability as one of the factors for assessing the quality of mobile health applications (mHealth apps). This is important as it assist mHealth apps developers to be able to design better and more marketable apps in an already congested market. There currently exist numerous usability techniques that has been used successfully over the years to determine how usable an app is. Popular usability attributes include satisfaction, efficiency, and effectiveness amongst others. It is realized some of these attributes are quantitative while others are subjective (qualitative) in nature such as satisfaction and attractiveness attributes. [8] claimed that most times quantitative attributes are usually based on user performance while subjective attributes are based on the way users view the app. Usability researchers have always had difficulty when making decisions on which technique to apply during usability evaluation purposes out of the numerous techniques that exist. It is realized that most of these techniques consume resources in terms of time and money. The problem is on how to evaluate numerous usability attributes at once, saving resources and also getting better results.

This work tends to approach usability evaluation from a wider perspective, taking numerous attributes into consideration as well as the quantitative and qualitative aspects simultaneously using MCDM techniques. The usability evaluation issue had been identified to be a Multi-Criteria Decision Making (MCDM) problem, which is a subset of the general Operational Research (OR) models that are used for solving problems involving high uncertainty and different ideas, data and information [33].

The MCDM problem is depicted by ranking or measuring each identified alternatives as they relate to their corresponding criteria. The MCDM problem aimed at choosing or deciding on suitable measurable usability constructs from various substitutes and criteria. The focus of this study is to rank all the 7 usability criteria and 23 sub-criteria identified in the usability hierarchical model by using the Analytic Hierarchy Process (AHP), a decision making technique which allows important ranking and prioritization to be done based on sets of multi-level criteria [21].

2.0 LITERATURE REVIEW

Making decisions can be described as a cognitive action that entails judging numerous available alternatives or options so as to choose the preferred alternative that will be effective as well as acceptable by decision makers [30].

Effective decision making is an action that involves a careful and systematic process in other for the main aim which is to select the best choice among numerous alternatives, is achieved. The general series of activities involved is highlighted in [5] article on decision making and this is also depicted in the MCDM procedures in Figure 1. MCDM has gained much popularity and has been widely used in different research areas as shown in Figure 2.

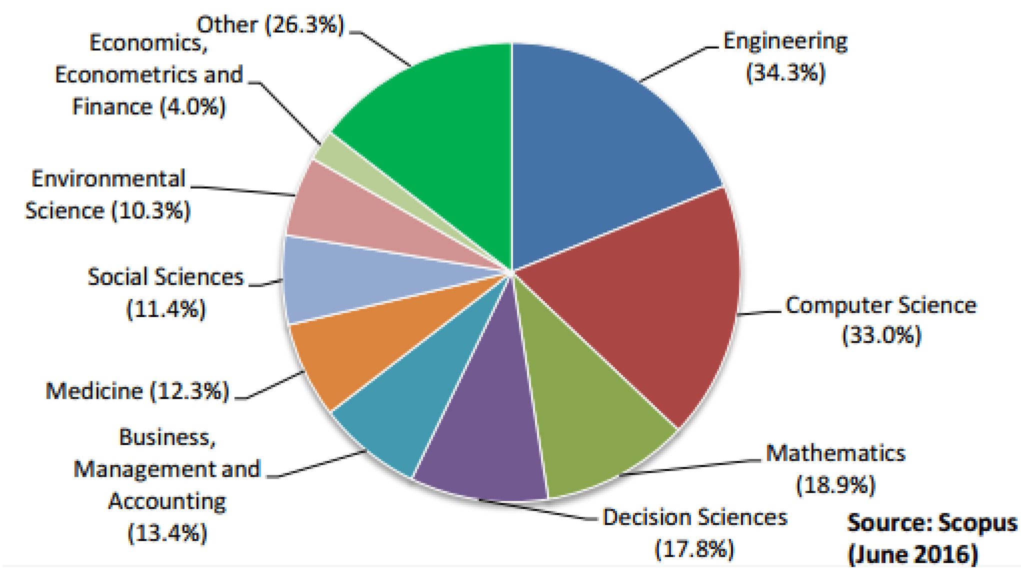

Figure 1: The spread of MCDM technique areas (Scopus database, 2016 as cited in [22])

In situations whereby a single attribute is to considered, this is termed single criterion decision making while where many attributes are involved, this is termed multi criteria decision making (MCDM). The multi-attribute decision-making problem has been found to be of high theoretical value and has been applied in different research areas both in the academia and industry [9].

MCDM techniques can take decisions in cases where conflicting multiple criterion exists and it can efficiently take care of both the quantitative and qualitative choices. It also has the ability to merge historical data and expert judgements by measuring subjective opinions [20]. MCDM can be grouped as either Multi Objective Decision Making (MODM), Multi Attribute Decision

Making or a combination of both and over the years, different MCDM techniques have been theorized as depicted in the hierarchical structure in Figure 2.

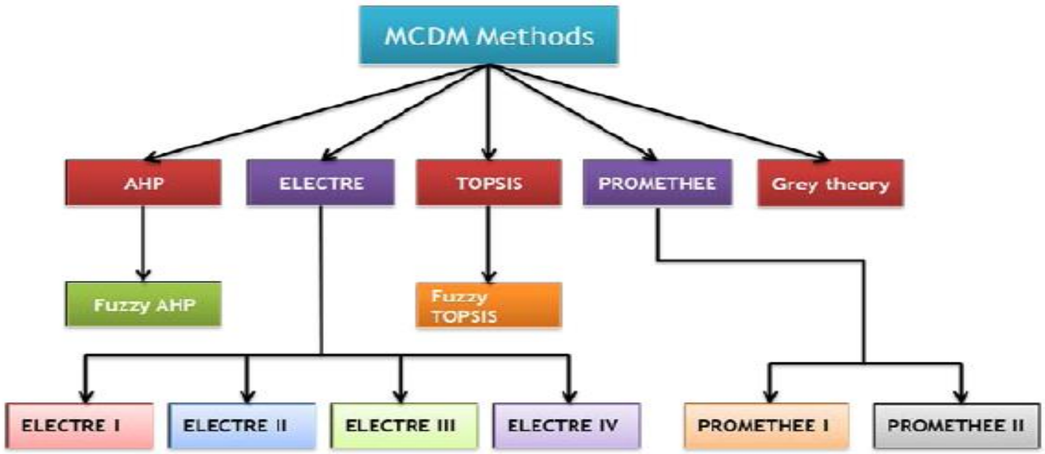

Figure 2: Various MCDM methods [1]

Other methods include the Multi Attribute Utility Theory (MAUT), Data Envelope Analysis (DEA), Goal Programming (GP), Analytic Network Process (ANP), Simple Additive Weighing (SAW), Technique or Order of Preference by Similarity to Ideal Solution (TOPSIS), Simple Multi-Attribute Rating Technique (SMART), Elimination and Choice Translating Reality (ELECTRE I, II, III and IV) Group, Fuzzy set theory, Preference Ranking Organization Method for Enrichment Organization (PROMETHEE I and II), Case Based Reasoning (CBR) and VlseKriterijusca Optimizacija I Kompromisno Resenje in Serbian (VIKOR). These techniques can also be categorized broadly into three sections as outlined by [32]:

i. Value measurement models: For these types of models, a crisp value for each alternative is measured and a weight w, which denotes the significance of the criterion is assigned to each criterion. Examples include SAW and AHP.

ii. Goal and reference level models: These models assess how good alternatives reach established goals. TOPSIS is a good example of this.

iii. Outranking models: These models assess the alternatives pairwise for each criterion by discovering the strength of selecting one over the other. Examples include ELECTRE and PROMETHEE.

Out of all these methods, the most widely used is the AHP, developed by Saaty and inspired by man's cognitive abilities [12]; [15]; [29]. There exist numerous MCDM techniques, each with its own benefits and limitations but basically to a new researcher who wants to make good decision based on the application of these techniques, the challenge is on how to choose the appropriate one that would be suitable in solving the problem at hand.

Few researches have been done to identify the differences between these techniques and to identify which one to apply for a particular situation. Most of these techniques can analyze both objective and subjective problems simultaneously. They can also deal with complex problems involving many conflicting criteria. Researchers have tried to solve this problem by doing comparative analysis on some techniques based on the problems they want to solve but some of these methods require very complex calculations and doing such analysis could be time consuming and totally different results could be gotten leaving such researchers more confused. There is also the assertion that it is not easy to group and assess various MCDM techniques because most of them use different theories relating to judgement maker's choices and varieties of information affecting those choices.

This implies that choosing appropriate MCDM technique that would perform optimally, choose the right alternative by providing the right order and rank becomes an issue on its own. [27] tried to overcome this limitation by reviewing numerous attempts at comparing MCDM techniques by other researchers so as to provide a cogent solution to this issue. As a result, a more simplified but systematic way of choosing an appropriate MCDM technique that can be used to solve a problem under study was proposed by making use of 16 evaluation criteria to compare and evaluate MCDM techniques before finally making a valid and more reliable choice when dealing with any complex decision problems.

To summarize the framework, it was asserted that a technique should be reliable, easy to use, be able to represent any problem in a hierarchy, provide a logical/mathematical procedure to solve such problems, justifiable, have a way of checking the consistency in decision makers opinions, be able to ascribe weights to all criteria/alternatives in a given problem, possess some technique to scale/rate decision makers opinions, be able to deal with or avoid rank reversal issues, have some way of synthesizing and validating decision makers judgements. Lastly a MCDM technique should be trustworthy, efficient and be able to predict the outcome of decision makers' opinions.

2.2 Analytic Hierarchy Process (AHP)

AHP is a useful mathematical technique that is used to solve MCDM problems, where a choice has to be made from a number of alternatives based on their relative importance [2]; [31]. It was developed by Saaty in the 70's from mathematical and psychological principles. It relies on the judgments of experts to derive priority scales through pairwise comparison of decision elements at each level as shown in Figure 3.

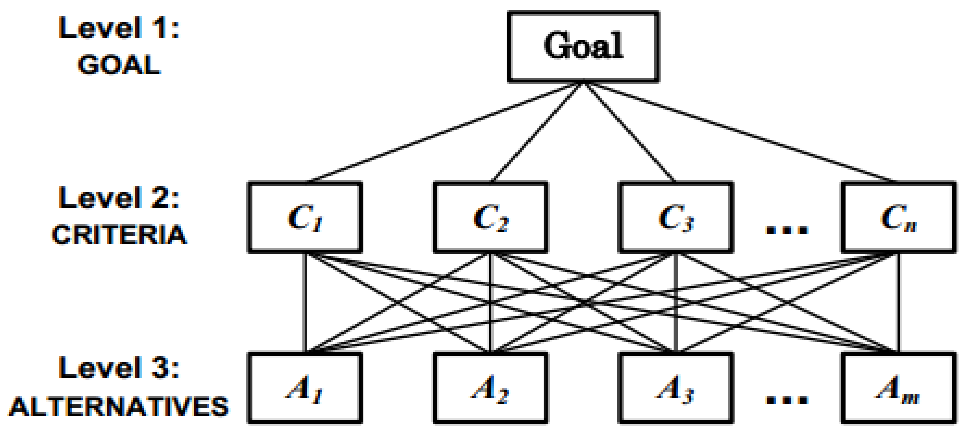

Figure 3: Hierarchical Decision Structure [3]

It enables the development of numerical score or weight to rank each decision alternative based on criteria and the computation of consistency ratio to ascertain the reliability of the comparative judgments represented in the comparison matrix. [12] gave a detailed review of AHP, application areas and developments since its inception in the 70s.

It is easy to apply, popular, scalable since it allows for problems to be represented hierarchically. Weighing and comparing alternatives is done easily by decision makers using this approach [4]. Highlighted are the major procedures involved in AHP technique according to its proponent, [24]; [25]:

i. Define the unstructured problem based on the criteria and alternatives.

ii. Construct a set of pair-wise comparison matrices among decision elements i and j by establishing priorities among them based on a preference scale.

Let a_{ij} (i, j=1,…, n) denote the relative weight of alternative i to j, and $a_{ji} = 1/a_{ij}$, then the corresponding matrix is n x n matrix (a_{ij}), where $a_{ii} = 1$ for all i=1,…, n.

$$A' = \begin{bmatrix} 1 & a_{12} & & a_{1n} \\ a_{21} & \dots & a_{ij} & \dots \\ \dots & a_{ji} = 1/a_{ij} & \dots & \dots \\ a_{n1} & \dots & \dots & 1 \end{bmatrix} \qquad \text{Equation (1)}$$

where a_{ij} is the comparison between element i and j

In forming the pairwise matrix, if a certain criteria or alternative is compared with itself, then the weight given to such comparison will be 1.

Table 3 gives Saaty's 9-point scale for pairwise comparison which is used by experts to explain how an alternative is ranked over the other. It is claimed by some researchers that the technique is prone to subjectivity, imprecision and it cannot be used to denote some comparison where alternatives are more than 9 points [29].

Table 1: Pairwise Comparison Scale (Saaty, 2008)

Saaty's scale	**Definiton**
1	Two criteria or alternatives have the same level of importance or the same weight
3	A criteria or alternative has a fair chance of being preferred over the other based on decision makers opinion i.e. reasonably important.
5	A decision maker is highly convinced that a criteria or alternative is preferred over the other
7	It is obvious that a criteria clearly dominates the other based on practice and decision makers opinion
9	The proof that a criteria or alternative is favored over the other is of topmost imaginable order and assertion.
2,4,6,8	These are chosen in situations when decision makers opinion about a criteria or alternative being preferred over the other are of average values i. e. when they need to find a middle ground between two criteria or alternatives.
Reciprocals	If a criteria a for example, already has a value ascribed to it when compared with another criteria b, then b automatically has the inverse or reciprocal value when judged with a.
Rational (1.1 – 1.9)	These values are chosen when decision makers find it cumbersome to ascribe the best values in a certain situation but when assessed with criteria that differs, it will not be too obvious to notice the magnitude of the small value but the significant of such criteria can still be known.

Various researchers have also proposed other judgement scale types as shown in Table 2 but Saaty's linear scale type is still the most widely applied in AHP [7].

Table 2: Different Judgement Scale Types [12]

Author	Year	Scale type	Mathematical definition	Parameters	Approximate scale values
Saaty	1977	Linear	$s = x$	$x = \{1,2,\ldots,9\}$	1;2;3;4;5;6;7;8;9
Harker and Vargas	1987	Power	$s = x^2$	$x = \{1,2,\ldots,9\}$	1;4;9;16;25;36;49;64;81
Harker and Vargas	1987	Root square	$s = \sqrt{x}$	$x = \{1,2,\ldots,9\}$	$1; \sqrt{2}; \sqrt{3}; 2; \sqrt{5}; \sqrt{6}; \sqrt{7; \sqrt{8; 2}}$
Lootsma	1989	Geometric	$s = 2^{x-1}$	$x = \{1,2,\ldots,9\}$	1;2;4;8;16;32; 64;128;256
Ma and Zheng	1991	Inverse linear	$s = \frac{9}{10 - x}$	$x = \{1,2,\ldots,9\}$	1;1.13;1.29;1.5;1.8;2.25;3;4.5;9
Dodd and Donegan	1995	Assymptotical	$s = \tan^{-1}\left[\frac{\sqrt[3]{(x-1)}}{14}\right]$	$x = \{1,2,\ldots,9\}$	0;0.12;0.24;0.36; 0.46;0.55;0.63;0.7;0.76
Sal Hamalainen	1997	Balanced	$s = \frac{w}{(1 - w)}$	$w = \{0.5;0.55;0.6;\ldots..9\}$	1;1.22;1.5;1.86;2.33;4;5.67;9
Ishizaka, Balkenborg and Kaplan	2010	Logarithmic	$s = \log_2 (x + 1)$	$x = \{1,2,\ldots,9\}$	1;1.58;2;2.2;2.58;2.81;3;3.17;3.32

Based on Table 1, a reciprocal matrix A can be developed as shown in equation 1 whose values represent the dominance of *i*th element on *j*th element

1. $a_{ij} = 1/a_{ji}$, for $a_{ij} \neq 0$
2. $a_{ij} = 1$ for $i = j$ and $i, j = 1, 2, \ldots\ldots..,n$

iii. Compute the consistency ratio to determine the acceptability or otherwise of the chosen criteria or alternative. This is given in equation 2

$$CI = \frac{\lambda_{max}}{n - 1} \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_Equation (2)}$$

where n is the dimension of the matrix, λ_{max} is the maximal eigenvalue and *CI* is the Consistency Index. Hence, Consistency Ration CR = CI/RI where RI is the Random Index (the average CI of 500 randomly filled matrices).

If CR is less than 10%, then the matrix can be considered as having an acceptable consistency. [23] calculated the random indices as shown in Table 3 for $n \leq 10$ and it is still the most acceptable and widely utilized RI Table among AHP researchers.

Table 3: Random Indices [23]

N	3	4	5	6	7	8	9	10
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

iv. Estimate the relative weights of the decision elements using eigenvector method. Saaty developed the eigenvalue method in order to synthesize a pairwise comparison matrix A and to obtain a priority vector for several decision criteria and alternatives.

Vector of weights is generated as normalized eigen-vector using equation 3

$$Aw = \lambda_{max}w \quad \text{\_\_\_\_\_\_\_\_\_\_Equation (3)}$$

where λ_{max} denotes the eigenvalues and relative vector weight is given in equation 4

$$w = [w_1 w_2 \ldots\ldots\ldots w_n]^T \quad \text{\_\_\_\_\_\_\_\_\_Equation (4)}$$

v. Aggregate the relative weights: For group decision, numerous researchers usually recommend geometric mean techniques instead of the arithmetic mean [14] but [34] also confirmed in their study that using geometric mean for aggregate calculation could be difficult for large number of experts and in this case, the arithmetic mean is suitable. [19] gave a detailed review on different aggregation methods for AHP and under which condition to choose any in their article on comparative analysis on aggregation techniques for both AHP and ANP models.

vi. Model Synthesis: After the local priorities have been gotten which signifies the preferred choice with respect to each criterion, the overall priority otherwise known as the final priority for each alternative has to be calculated i.e. priorities that takes into consideration not only the preferred choice for each criterion but also the fact that each criterion has a different weight [17].

vii. Sensitivity analysis: This is done to understand how robust, reliable and implementable the final model is [26]; [27]. It is achieved by making some changes to the weights of the criterion and determine how they affect the overall priorities of the alternatives.

viii. Make a final decision after all the steps have been rigorously done by comparing the overall priorities gotten and whether there is any significant difference for a clear choice to be made. It is also required to analyze the result of the sensitivity analysis.

AHP as a MCDM technique is a powerful tool for solving, ranking, selection and comparison problems especially when it relates to decision making.

3.0 METHODOLOGY

The MCDM optimization model applied in this work was used to rank usability attributes based on their weights for efficient decision making by developers to optimally minimize resources used for mHealth application development. This type of models are also called prescriptive models as they aim to prescribe what decision makers ought to do in order to get an optimal solution [6]. It also serves as a decision support model for stakeholders involved in mHealth applications development.

3.1 Usability Hierarchical Model

The usability criteria and sub-criteria used in this study were all based on the PACMAD and the IMM models. [10] proposed the PACMAD model by combining the ISO 9241-11 [13], Nielson’s model [18] and added the Cognitive load attribute which directly affects the mobile context in which an application is being used. The resulting hierarchical model is shown in Figure 4.

The other usability model that was considered is the Integrated Measurement Model (IMM) by [11], which combined different qualitative and quantitative usability constructs from numerous models.

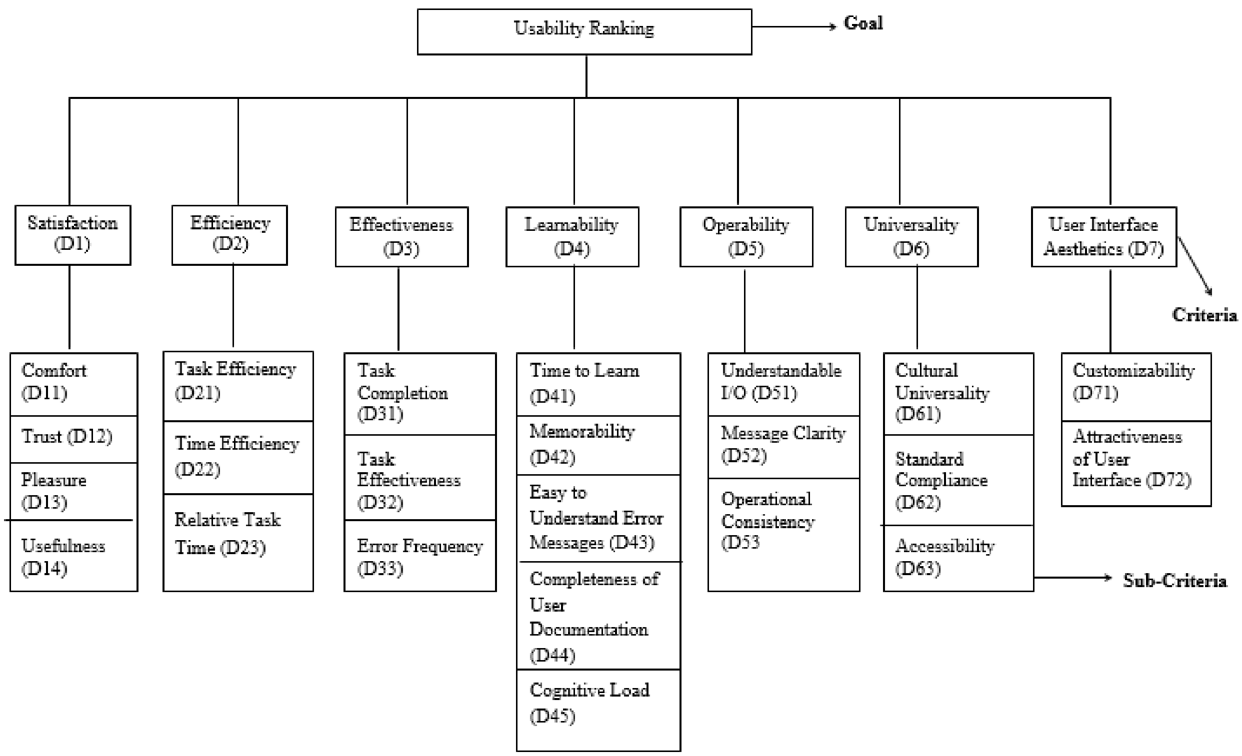

Figure 4: Hierarchical Usability Model

3.1.2 MCDM Model Approach

Usability evaluation has been identified as a MCDM problem as ascertained by numerous works reviewed in the previous chapter. Figure 5 gives the detailed process of how to solve the problem and proffer an effective and reliable result to help persuasive mHealth designers make the right decision when it comes to developing highly usable product

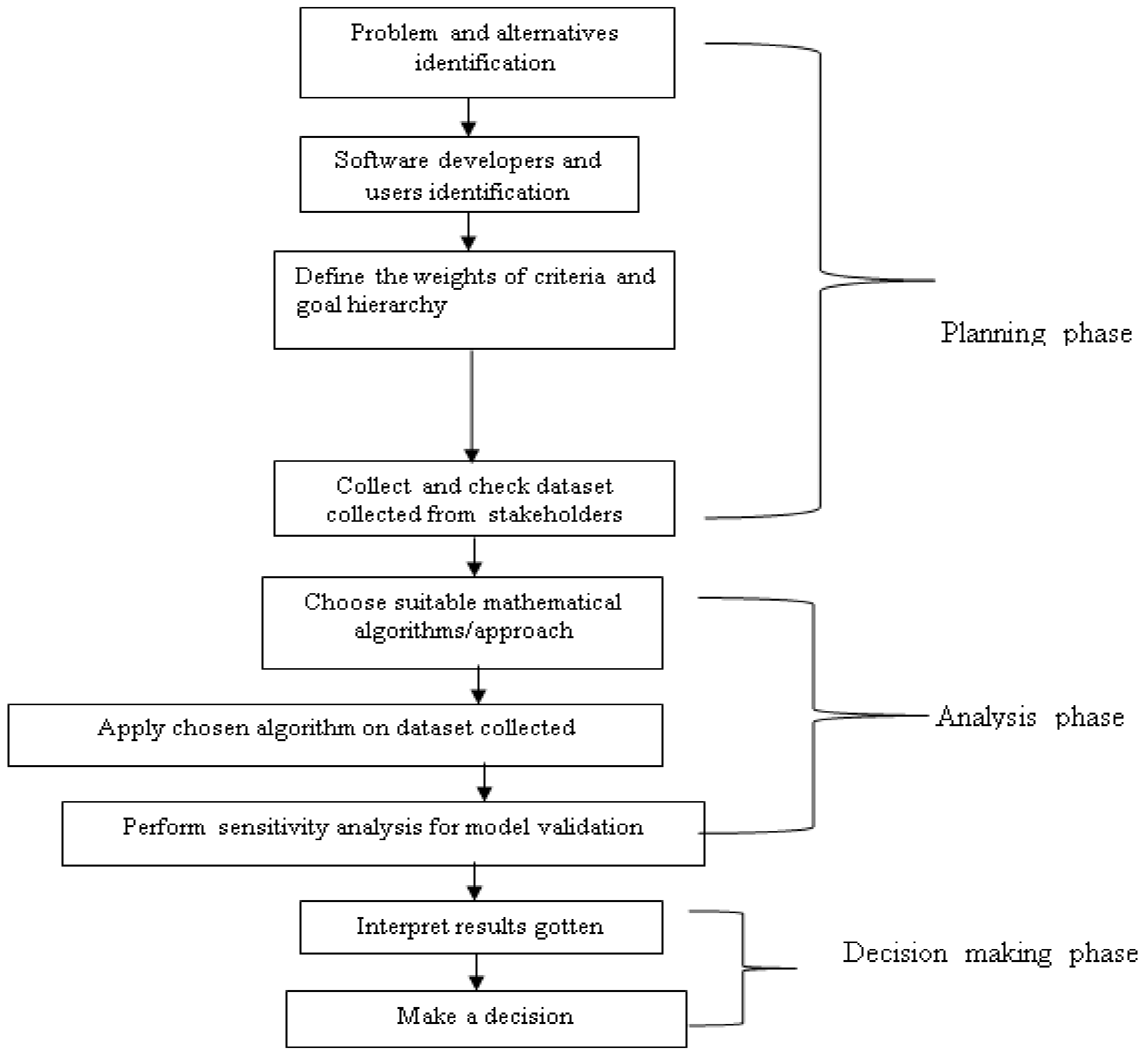

Figure 5: Schematic diagram for MCDM approach

Usability Problem Identification and Formulation

A general multi-criteria decision problem with m alternatives A_i (i=1, 2, …., m) and n criteria C_j (j=1, 2,……, n) can be briefly expressed as:

$D = [x_{ij}]_{m \times n}$ and $W = [w_j]_n$, where i= 1,2,……,m and j=1,2,…..,n. ____________Equation (5)

In equation (5), D is the decision matrix (where x_{ij} denotes the rating or performance of *i*-th alternative A_i with respect to *j*-th criterion C_j), and W is the the weight vector (where w_j denotes the weight of *j*- th criterion C_j, m is the number of compared alternatives and n is the number of the criteria).

From the usability hierarchy in Table 6, the main goal is to get a crisp usability value after evaluation. Priority weights were given to each criteria and sub-criteria for optimized decision making.

Sample data was obtained purposively and randomly both from the Academia and independent software developers as a result of the sensitive and complex nature of the measuring tool. It was required that respondents understand some basic computer science principles, app design and the meaning of each criteria and sub-criteria specified in the usability model.

Sample size for model evaluation was determined by making use of the usability sample size calculator, a tool designed by [28] based on usability pragmatic, usability sample size determination theoretical concepts and experience on user research studies. Results of calculation yielded 22 as the sample size.

4.0 RESULTS AND DISCUSSION

4.1 Usability Ranking Group Consensus Results

The data in Table 4 shows the percentage and level of agreement or consensus of all judgements made on which usability criteria and sub-criteria are mostly preferred or should be considered when designing a mHealth app by all the 22 participants.

Table 4: Group Consensus Results

Node	Group CR (%)	AHP Group Consensus (%)	AHP-OS Scale
Usability Ranking	1.9	78.2	High
Satisfaction	0.6	84.0	High
Efficiency	0	43.8	Very Low
Effectiveness	0.3	52.5	Low
Learnability	1.8	73.4	Moderate
Operability	0.1	73.7	Moderate
Universality	0.4	69.8	Moderate
User Interface Aesthetics	0	40.0	Very Low

AHP-OS Scale: Below 50%: Very low (Disagreement); Low: 50%-65%; Moderate: 65%-75%; High: 75%-85%; Very High: Above 85%

CR < 10%: Acceptable Consistency in judgements made as a group

Overall AHP Group Consensus: 68% which is moderate

Table 5 shows the group results of the usability hierarchy with consolidated priorities.

Table 5: Hierarchy with Consolidated Priorities

Level 0	**Level 1**	**Level 2**	**Global Priorities (%)**
	D1 = 0.062	D11 = 0.086	0.5
		D12 = 0.550	3.4
		D13 = 0.081	0.5
		D14 = 0.283	1.8
	D2 = 0.303	D21 = 0.444	13.4
		D22 = 0.226	6.9
		D23 = 0.330	10.0
	D3 = 0.267	D31 = 0.335	8.9
		D32 = 0.514	13.7
		D33 = 0.150	4.0
Usability Ranking	D4 = 0.099	D41 = 0.164	1.6
		D42 = 0.260	2.6
		D43 = 0.072	0.7
		D44 = 0.078	0.8
		D45 = 0.426	4.2
	D5 = 0.187	D51 = 0.176	3.3
		D52 = 0.149	2.8
		D53 = 0.676	12.6
	D6 = 0.033	D61 = 0.116	0.4
		D62 = 0.241	0.8

		D63 = 0.643	2.1
	D7 = 0.049	D71 = 0.337	1.6
		D72 = 0.663	3.3
			Total = 100

From usability criteria, based on the opinions of the 22 participants, Efficiency was ranked highest with 30%, followed by Effectiveness with 27%, Operability with 19%, Learnability with 10%, Satisfaction with 6%, User Interface Aesthetics with 5% and lastly Universality with 3% which ranked the lowest. The implication of this result on persuasive mHealth application is that during development, such app should be designed in a way that the ability of users to complete a task in a specified context is given maximum consideration. The apps tendency to take various users with different cultural backgrounds into cognizance should be given the least attention during design but not ignored.

Based on sub-criteria results, for Satisfaction criteria, Trust ranked the highest followed by Usefulness with 28%, Comfort with 9% while Pleasure ranked the lowest with 8%.

For Efficiency, Task efficiency ranked the highest with 44%, followed by Relative task time with 33% while Time efficiency ranked the lowest with 23%.

For Effectiveness, Task effectiveness ranked the highest with 51%, Task completion with 34% and Error frequency with 15%.

For Learnability, Cognitive load ranked the highest with 43%, Memorability with 26%, Time to learn with 16%, Completeness of user documentation with 8% and Easy to understand error messages with 7%.

For Operability, Operational consistency ranked the highest with 68%, Understandable I/O with 18% and lastly Message clarity with 15%.

For Universality, Accessibility ranked the highest with 64%, Standard compliance with 24% and Cultural universality with 12%.

For User Interface Aesthetics, Attractiveness of user interface ranked the highest with 66% while Customizability had the lowest rank with 34%.

Figure 6 shows the bar chart to indicate each consolidated global priority

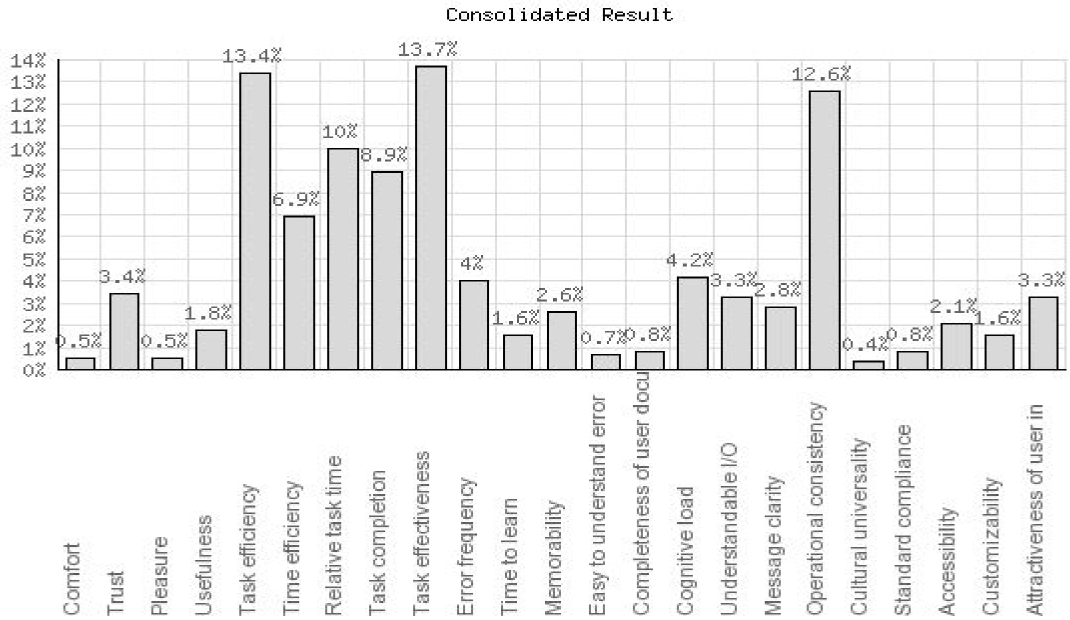

Figure 6: Consolidated Global Priority Bar Chart

5.0 CONCLUSION AND RECOMMENDATIONS FOR FURTHER STUDIES

The study ranked the criteria and cub-criteria in a usability hierarchical model using AHP, a technique based on mathematical and psychological principles. This approach was used as a result of the complex nature involved in evaluating both the quantitative and qualitative usability attributes simultaneously.

Relevant weights for all identified factors were determined using Saaty's eigenvalue and eigenvector approach. Opinions were elicited from 22 decision makers which comprised of mHealth developers and prospective mHealth apps users. Consistency ratio for all participants were computed to get reliable and valid opinions. The usability model was implemented using the AHP-OS. Based on results of analysis, efficiency had the highest rank with 30% followed by effectiveness with 27% while Universality ranked lowest with 3%.

The MCDM technique was found to be more efficient than the traditional methods of usability since numerous attributes were evaluated at the same time thereby saving cost, time and other resources. It was also realized that based on the findings of this study, the AHP was a helpful tool in enabling effective and efficient decisions to be made by users and developers of mHealth apps about the usability attributes they would want integrated into a system at the developmental stage.

In developing a mHealth app, based on the findings of this work, usability attributes like efficiency, effectiveness and operability should be more focused on, while attributes like learnability, satisfaction, user interface aesthetics and universality should also be considered but given less priorities in future studies. The MCDM utilized for evaluation purpose in this research presented a well-structured, scientific and critical approach at solving complex usability evaluation problems. The technique also presented a mathematical, psychological and logical way for making efficient decision during the usability evaluation of mHealth apps**.** This research paves the way for future research to consider additional important usability factors and involve more decision makers in the opinion elicitation process both from the Industry and the Academia.

It is recommended that software/apps designers could use the developed model to evaluate the usability of other types of software applications or systems aside mHealth apps to predict and ensure their usability during and after system development to save developmental resources and cost. Based on the results of evaluation, it is also recommended that the usability criteria/sub-criteria with low weights or ranks should be more focused on during further prototype design. This study can be extended by considering other usability attributes or factors that are essential during and after system development. More respondents can also be involved in the opinion gathering process to get judgements from a larger group of decision makers to make more valid judgements. More so, there is a need to develop better MCDM tools for model implementations that can incorporate and at the same time will be able to compare two or more MCDM techniques at the same time. Furthermore, it is suggested that evaluation can also be done using other Multi-criteria Decision Making (MCDM) approaches and for the results obtained to be compared so as to be able to determine the differences or relationships between other MCDM techniques on usability models.

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