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An Evaluation Methodology for Ergonomic Design of Electronic Consumer Products Based on Fuzzy Axiomatic Design

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The development life cycle of software and electronic products has been shortened by the growth of rapid prototyping techniques. The evaluation of electronic consumer products should consider hardware and software as well as the ergonomic usability, emotional appeal and aesthetic integrity of the design. This research follows a systematic approach to develop an evaluation methodology for electronic mobile products on ergonomic design. The proposed methodology is based on fuzzy multi attribute decision making and fuzzy axiomatic design realized in three steps; determination of ergonomic attributes for electronic consumer products, determination of a representative set of alternatives, and selection of the best alternative in terms of ergonomic design by utilizing fuzzy axiomatic design. A case study is also provided to support the proposed methodology.

Keywords: Fuzzy Axiomatic Design, Ergonomic Designs, Multi Attribute Decision Making, Electronic Consumer Products, Mobile Phone

1 INTRODUCTION

Usability has been an important criterion of decision making for end-users, consumers, product designers and software developers of consumer electronic products. Most of early studies on usability were about computer software applications, now interest is growing in relation to electronic consumer products. Usability dimensions for electronic consumer products are different from software products. Since they are made up both hardware and software, the characteristics of both sides should be considered when evaluating the usability of the products. The proposed methodology can be used for comparison of competing electronic mobile products in the end-user market.

Mobile phones as an electronic consumer product, have become widely used in all over the world. There are users from all age groups, all socioeconomic classes and all education levels. Besides, the functionality of the mobile phones is enhanced as the telecommunication and media technologies advance. Since mobile phones functions are expanded, the use of mobile phone has become a complex issue and various usability problems have arisen. Therefore, mobile phones are selected to be analyzed in the case study of the proposed methodology.

The proposed methodology is based on fuzzy multi attribute decision making and fuzzy axiomatic design realized in three steps; determination of ergonomic attributes for electronic consumer products, determination of a representative set of alternatives and selection of the best alternative in terms of ergonomic design by utilizing Fuzzy Axiomatic Design (FAD).

In this study, to make a comparison, initially dimensions of ergonomic mobile phones are decided. Then, a set of experts consisting of two ergonomics specialists and one user of the related alternative evaluated the six alternatives with respect to their ergonomic attributes. Next, expert opinions are aggregated using the aggregation methodology offered by Olcer and Odabasi [1]. Comparison of the mobile phones according to their ergonomic properties is conducted under the predetermined physical and mental criteria. Since the comparison of mobile phones regarding ergonomic concerns has incomplete information, FAD approaches are exploited to determine the phone with the best ergonomic design.

The paper is organized as follows: In Section 2, related literature review is provided. In Section 3, the proposed methodology is explained in detail. In Section 4, a case study of the proposed methodology is given. Finally in Section 5, conclusions and further suggestions are summarized.

2 LITERATURE REVIEW

The paper is trying to address the problem of evaluation of electronic consumer products in terms of ergonomic design, taking into account both physical and cognitive aspects, aggregating opinions of several experts in the area, and using multi attribute-fuzzy axiomatic design as a decision tool. Sears and Arora have compared two gesture recognition techniques, namely Jot and Graffiti, for mobile communication devices [2]. These two techniques are compared in terms of data entry rates, uncorrected errors, satisfaction and period of difficulty. The proposed study tries to compare electronic consumer products taking into account physical and cognitive aspects of ergonomics and analyzes evaluation of mobile phones as a case study.

Evaluation of electronic consumer products in terms of ergonomic design is complicated since this problem has multiple attributes that can be measured using crisp or fuzzy evaluations. According to Zadeh [3], fuzzy sets provide a much better model for systems in which human judgment and emotion play a dominant role. Regardless of the area or content application, fuzzy set approaches have always been one of the most appropriate tools when it is necessary to model the human knowledge.

Regardless of the level of human work, three types of fuzziness are present and should be accounted in human centered systems. The first type of fuzziness is due to our inability to collect all necessary information about a system. The second type of fuzziness is caused by the vagueness of the relationships between people and their working environments, and complexity of the rules and principles. The third one is emanated from human judgment behavior. Since Fuzzy set approach is concerned with mathematical representation and manipulation of degree of vagueness, it is the most appropriate model for the modeling of human centered systems [4].

Besides, there are limits of using the classical mathematical language in human factors area. Since classical mathematical language is based on dichotomous character of set theory, this would cause restrictions especially in human factors area. This is due to vagueness of the natural language and the fact that in empirical research, natural language can not be substituted by formal language [4]. Thus, in this study, fuzzy approach is used to model the human knowledge as a part of the evaluation process of ergonomic design.

All the previous discussions regarding uncertainty are very important to incorporate into ergonomic studies. So, in this study we used fuzzy approach during selection of ergonomic mobile devices.

In this study, a part of the problem analyzed includes fuzzy multiple attributive decision-making problem where fuzzy assessments as well as crisp evaluations and multiple expert opinions are considered. The multiple attribute decision making (MADM) methods are decision aids in evaluating and/or selecting the desired alternative from a finite set of alternatives, which are described by multiple attributes. Several experts evaluate these attributes and their evaluations should be aggregated.

In problems of group decision making in fuzzy environment, experts' opinions often conflict. It is important to aggregate the conflicting opinions in a fuzzy multiple attributive group decision making problem.

Liang and Wang proposed a decision algorithm to solve the facility site selection problem under fuzzy environment. Using this algorithm, the decision makers' fuzzy assessments with various rating attitudes and the trade-off among various selection attributes can be taken into account in the aggregation process [4].

Chang and Chen proposed a decision algorithm based on fuzzy set theory and hierarchical structure analysis to solve the technology transfer strategy selection problem, where the linguistic variables and fuzzy numbers are used to aggregate the decision makers' subjective assessments about attribute weightings and appropriateness of alternative transfer strategies versus selection attributes to obtain the final scores called fuzzy appropriateness indices [6].

Olcer and Odabasi propose a fuzzy multi attribute decision making method which is composed of three stages, namely, rating, attribute based aggregation, and selection. In rating stage, each expert gives his/her opinions (which are generally fuzzy) about alternatives with respect to each subjective attribute. In attribute based aggregation, weights of attributes as well as degree of importance of experts are assigned. Subsequently, under each subjective attribute all performance ratings are aggregated for each alternative. Finally, all fuzzy elements of the aggregated decision matrices are defuzzified. The result of this phase is a decision matrix, which contains only crisp data. Then the alternatives of the problem are ranked by TOPSIS (technique for order preference by similarity to ideal solution) method [1]. In this study, the aggregation method proposed by Olcer and Odabasi is utilized.

AD aims to establish a scientific basis for design and to improve design activities by providing the designer with a theoretical foundation based on logical and rational thought processes and tools [7]. In order to achieve this aim, AD provides a systematic search process through the design space to minimize the random search process and determine the best design solution among many alternatives. AD applications have been applied in designing products, systems, organization, software and flexible manufacturing systems for ten years, and all these studies show the applicability and benefits of AD [8, 9]. So, in this paper, ergonomic mobile phone selection is justified by fuzzy AD approach.

3 PROPOSED METHODOLOGY

In this study, a three step procedure is proposed to select the best ergonomic design of any electronic device under concern. In the first step, the ergonomic attributes of the related area are determined with the help of ergonomics literature. After that, the attribute measures that will be used in the evaluation process are determined. In the second step, alternatives are evaluated by the domain experts. In this step, firstly, a set of alternatives is constructed. Then, regarding this set of alternatives, experts' opinions on alternatives are gathered taking into account the ergonomic attributes determined in the first step. Then an aggregation process proposed by Olcer and Odabasi [1] is utilized to aggregate the opinions of experts. In the third and final step, fuzzy axiomatic design is used to select the best ergonomic design. The flowchart of the proposed methodology can be seen in Figure 1.

The proposed model is expected to help designers to evaluate the usability of consumer electronic products. The steps of the proposed methodology are explained in detail in the following subsections.

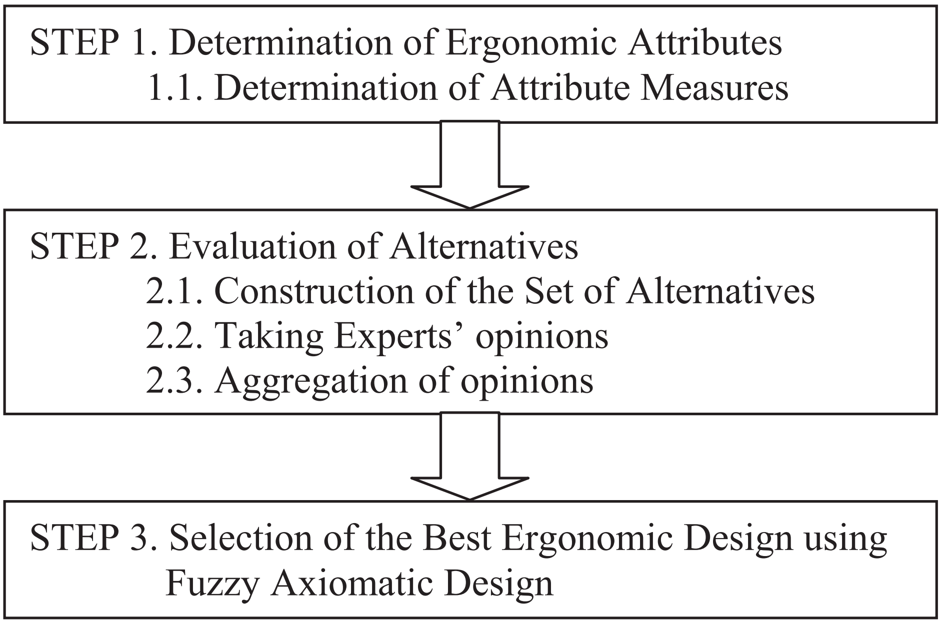

FIGURE 1
Steps of the proposed methodology.

3.1 Determination of Ergonomic Attributes and Their Measures for Electronic Consumer Products

Electronic consumer products can be defined as products which support wireless access and mobility in the user hands. Mobile phones, smart phones, Personal Digital Assistants (PDAs), and Handheld Personal Computers are some examples of electronic consumer products. Gorlenko and Merrick [10] provided the schematic representation of electronic consumer products' definition (see Figure 2). According to this diagram, the intersection area of mobile devices and wireless devices shows the scope of electronic consumer products.

Usability has been an important criterion of decision making for end-users, consumers, product designers and software developers of consumer electronic products. Most of early studies on usability were about computer software applications, now interest is growing in relation to electronic consumer products. Usability dimensions for electronic consumer products are different from software products. Also, according to Kjeldskov and Stage, current concepts, methodologies, and approaches in Human – Computer Interactions are challenged by the increasing focus on wearable, handheld, and mobile computing devices [11]. Since electronic consumer products are made up both hardware and software, the characteristics of both sides should be considered when evaluating the usability of the products.

Multiple attribute decision analysis starts with the generation of the attributes. Determination of the attributes is critically important to the final ranking and thus should be done very carefully. The attributes should be complete and exhaustive, contain mutually exclusive items and be restricted to

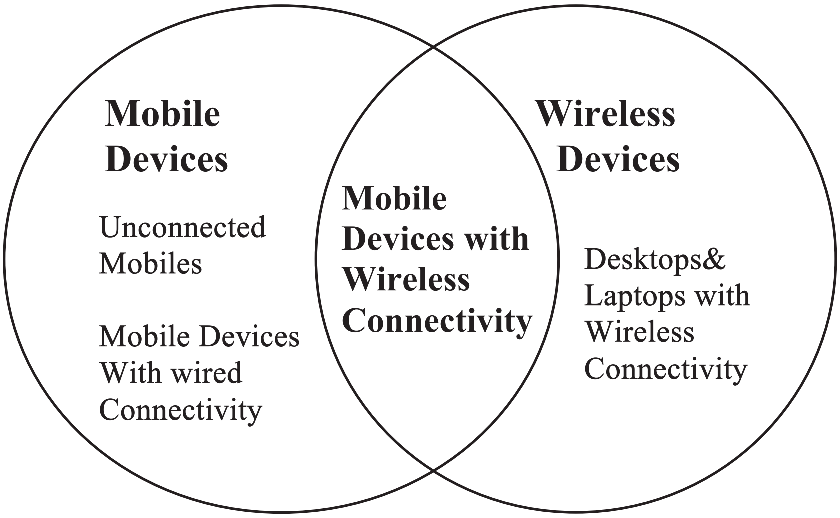

FIGURE 2
Schematic representation of electronic consumer products.

performance attributes of the highest degree of importance. In the following subsection determination of attribute measures is examined in detail.

In this study, where human interaction is the focal point, multiple attributes, namely physical and cognitive attributes, which may be assigned crisp or fuzzy valuations respectively, are used. The problem involves vagueness and fuzziness; the decision maker has a difficult task of choosing among the many alternatives to specify the best alternative. The characteristics of the alternatives are represented by interval-valued fuzzy sets because, in many cases, the decision maker has inexact information about the alternatives with respect to an attribute.

There are basically two types of attributes for a selection problem, namely 'subjective' and 'objective' attributes. If an assessment for an alternative with respect to an attribute is crisp, this attribute is objective. Such ratings do not change from one expert to the other. When experts' opinions for an alternative with respect to an attribute are fuzzy assessments, which can be different or identical, then the attribute is subjective.

The ratings of the experts especially when evaluating according to a cognitive attribute, are generally in fuzzy form. The fuzzy data can be linguistic terms or verbal assessments. This kind of qualitative data can be better modeled by fuzzy numbers.

3.2 Determination of Set of Alternatives

The set of alternatives are determined by the researchers, taking into account all of the models in the market and classifying them in terms of their different characteristics. Following that, representative examples are selected as alternatives to be evaluated if no other alternative is especially required to be evaluated.

3.2.1 Experts' Evaluation of Alternatives

Domain experts are asked to evaluate each alternative according to the attribute set determined. To use in the evaluation, also the attribute measures are provided. Each alternative is evaluated according to each attribute. As a result, an evaluation matrix of attributes and the respective expert evaluations for each alternative is obtained.

3.2.2 Aggregation of Experts' Evaluations

In this step, an attribute based aggregation approach for the group of experts under each subjective attribute is utilized. Aggregation is based on each subjective attribute. When more than one expert is involved in the selection problems, each expert might have a different weight. Therefore, attribute based expert weighting is a necessity and the degree of importance of each expert should be considered in the aggregation procedure. There are many methods for assigning attribute weights such as weighted evaluation technique (WET), eigenvector method, the entropy method, and etc. WET modeling aspect is to consider the existence of a moderator that assigns a weight to each expert. First, the most important person is selected among experts. Then the ith expert is compared with the most important person and a relative weight for the ith expert is determined. The final step of the weighting procedure is to normalize the relative importance of experts. In some cases, the relative importance of experts is widely different for each attribute, so the weights of experts are decided separately for each criterion. In this step, the aggregation procedure proposed by Olcer and Odabasi [1] is utilized to combine the experts and their evaluations. The steps of the aggregation method are given in Table 1.

3.3 Selection of the Best Alternative Using Fuzzy Axiomatic Design

Axiomatic Design is a guide for understanding design problems, while establishing a scientific foundation to provide a fundamental basis for the creation of products and processes [7]. The most important concept in axiomatic design is the existence of the design axioms. AD has two design axioms: the Independence Axiom and the Information Axiom [10].

The Information Axiom indicates that the best design is the one with the least information content. In order to apply axiomatic design theory, firstly information content for a given functional requirement FR^i must be calculated. Information content I^i is calculated according to the following equation:

$$\mathrm{I}^i = \log_2\left(\frac{1}{p^i}\right), \qquad (1)$$

In this formula, p^i is the probability of supplying FR^i and it is decided by the design range and system range. Design range shows what the designer wishes to achieve in terms of tolerance, and system range shows the system capability. The intersection area between design range and system range shows

1. Translate each trapezoidal fuzzy number (TFN) to standardized fuzzy number

2. Calculate the degree of agreement (or degree of similarity) $S_{ij}(R_i, R_j)$ of the opinions between each pair of experts E_i and E_j, where $S_{ij}(R_i, R_j) \in [0, 1]$, $1 \leq i \leq M$, $1 \leq j \leq M$, and $i \neq j$. A and B be two standardized trapezoidal fuzzy numbers, $A = (a_1, a_2, a_3, a_4)$ and $B = (b_1, b_2, b_3, b_4)$ where $0 \leq a_1 \leq a_2 \leq a_3 \leq a_4 \leq 1$ and $0 \leq b_1 \leq b_2 \leq b_3 \leq b_4 \leq 1$. Then the degree of similarity between the standardized trapezoidal fuzzy numbers A and B can be measured by the similarity function S, $S(A, B) = 1 - \frac{|a_1-b_1|+|a_2-b_2|+|a_3-b_3|+|a_4-b_4|}{4}$ where $S(A, B) \in [0, 1]$. The larger the value of $S(A, B)$ the greater the similarity between the standardized trapezoidal fuzzy numbers A and B. It should be noted that $S(A, B) = S(B, A)$

3. Calculate the average degree of agreement $AA(E_i)$ of expert $E_i (i = 1, 2, \ldots, M)$

$$AA(E_i) = \frac{1}{M-1} \sum_{\substack{j=1 \\ j \neq 1}}^{M} S(R_i, R_j)$$

4. Calculate the relative degree of agreement $RA(E_i)$ of expert $E_i (i = 1, 2, \ldots, M)$, where

$$RA(E_i) = \frac{AA(E_i)}{\sum_{i=1}^{M} AA(E_i)}$$

5. Calculate the consensus degree coefficient $CC(E_i)$ of expert $E_i (i = 1, 2, \ldots, M)$, where $CC(E_i) = \beta \times we_i + (1 - \beta) \times RA(E_i)$ where $\beta (0 \leq \beta \leq 1)$ is a relaxation factor of the proposed method. It shows the importance of the we_i over $RA(E_i)$. When a homogeneous group of experts problem is considered, $\beta = 0$. The consensus degree coefficient of each expert is a good measure for evaluating the relative worthiness of each expert's opinions.

6. Finally, the aggregation result of the fuzzy opinions is R_{AG} as $R_{AG} = CC(E_1) \otimes R_1 \oplus CC(E_2) \otimes R_2 \oplus CC(E_M) \otimes R_M$, where operators $\otimes$ and $\oplus$ are the fuzzy multiplication operator and the fuzzy addition operator, respectively.

TABLE 1
Steps of the aggregation methodology

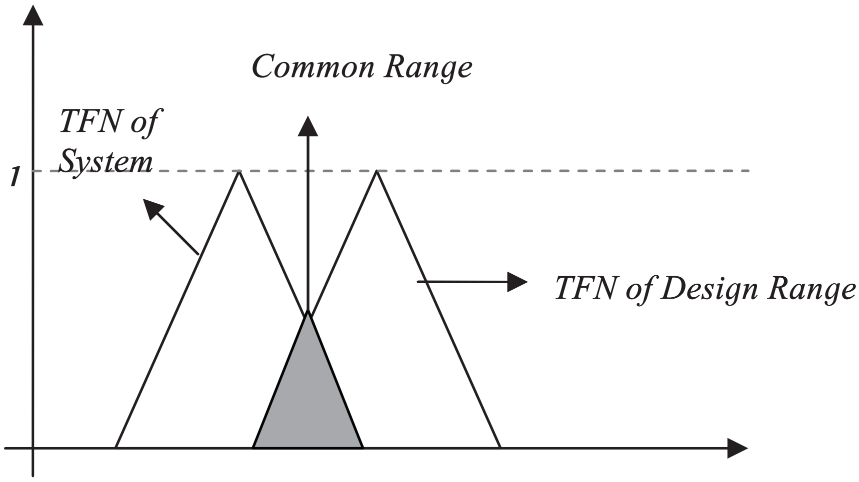

FIGURE 3
The common area between design range and system range.

the region where the acceptable solution exists and it is called common range. p^i is defined as follows:

$$p^i = (\text{system range}/\text{common range}) \tag{2}$$

After obtaining all I^i for each FR^i, because there are n FRs, the total information content is the sum of all probabilities. If I^i approaches infinity, then the system will never work [7].

In the fuzzy case, there is incomplete information about the system and design range, so the data available is fuzzy. The main advantages of using a fuzzy set are not only a gain in precision, but also the reduction of model complexity [8, 9].

The system and design range for a certain criterion will be expressed by using "over a number", "around a number" or "between two numbers". Triangular or trapezoidal fuzzy numbers can represent these kinds of expressions. We now have a function of triangular or trapezoidal fuzzy number whereas we have a probability density function in the crisp case. So, the common area is the intersection area of triangular or trapezoidal fuzzy numbers. The common area between design range and system range is shown in Figure 3 [8, 9].

Therefore the information content is equal to

$$I = \log_2\left(\frac{\textit{TFN of System Range}}{\textit{Common Area}}\right)$$

4 CASE STUDY: EVALUATION OF MOBILE PHONES IN TERMS OF ERGONOMIC DESIGN

In this study, mobile phones are chosen as the target products among electronic consumer products for two main reasons. It is estimated that

986 million phones will be sold in 2006, which is 21% more than 2005 [13]. Mobile phones have become one of the indispensable products in human life. They are not only communication devices, but also small entertainers in people's pockets. Their functions and audiovisual capabilities are enhanced everyday. As they become more talented, the time the people spend with their mobile phones increase inevitably. That has made mobile phones our subject in terms of ergonomic design.

According to a recent survey from International Data Corporation (IDC), a personal use of mobile phones is a big part of consumers' lifestyle and also is on the rise [14].

Also, mobile phones functions have expanded day by day, now they can provide so many functions such as short messaging service, internet connectivity, mobile camera, video recording, mp3 player, etc. On the other side, mobile phone sizes are shrunk, and functions and options can not be efficiently displayed on a small screen. By a hierarchical menu system, this problem tried to be overcome, but a standard hierarchical menu has not become on the market yet [16]. Also, a study on which design characteristics compel users and cause errors [17] shows that there are mainly three categories in which the user errors can be classified in a hierarchical menu system: user chooses the wrong option, user proceeds in the wrong direction of submenus, and user thinks that s/he has chosen the wrong option even if s/he has chosen the right one. The weak factors of design that compel the users most are weak categorization of functions, low differentiation of different options on the same menu, locating logically close functions under different submenus, and use of generic terms. Shrinking screens with respect to increasing complicated functions constitute an important problem on the ergonomic design of mobile phones [18]. So, the use of mobile phone has become a complex issue and various usability problems have arisen.

4.1 Determination and Fuzzification of Ergonomic Attributes for Mobile Phones

Previous research on Ergonomic Mobile Phones has been done along two separate lines: cognitive approach and physical approach. Cognitive approaches focus on cognitive factors of mobile phone's menu structure, and its affect on end user behaviors, and performance in information retrieving. Physical approach focuses on design elements such as weight, dimension, screen size and arrangement of buttons.

Cognitive approach is interested in usability criteria such as learnability, memorability, efficiency, and image.

Three usability dimensions are defined in ISO/IEC 9241-11: effectiveness, efficiency and satisfaction. Effectiveness is defined as the accuracy and completeness with which users achieve specific goals. Efficiency is about the resources expended in relation to the accuracy and completeness with which users achieve specific goals, and satisfaction is the subjective assessment of how pleasurable it is to use. Addition to these factors, learnability (ability to reach a reasonable level of performance) and memorability (ability to remember how to use a product) is defined by Nielsen [15, 16].

Another reference for usability dimension is SUMI which provides a usability profile according to five scales: affect, control, efficiency, helpfulness, learnability [19, 20]. Also, Han *et al.* [21] divided usability into two main groups. First one is defined as the performance dimensions that measure the user performance. The second group is defined as the image/imprecision dimension that measure the user's perception of the image and imprecision regarding to products. Moreover, the MPUQ (developed by Ryu) includes new criteria such as pleasurability and specific tasks performance.

While most of early studies of mobile phones focused on usability of hierarchical menu structure and are related with cognitive approach, there are limited studies about ergonomic design of physical features of a mobile phone. Actually cognitive and physical factors are not considered separately because they are related. For example, when usability of internet navigations in mobile phone is a cognitive factor, its usability depends on screen size which is physical feature, and there is trade off between these factors and they should be considered together. For this reason, in this study mobile phones are evaluated both by physical and cognitive factors together making a synthesis of these two approaches. Ergonomic features used in this study are listed in Table 2. Cognitive aspect's sub criteria are formed by the common factors in the existing usability questionnaires that are shown in Table 3. Lai *et al.* [22] determine three representative image words: Simple–Complex, Handsome–Rustic, Leisure–Formal. Since, experts' evaluations have so many factors, these three representative words are used in order to evaluate image of the mobile phone. Moreover, physical attributes are found to be one of the most important features in mobile design in Seva [23] and product catalogs. According to Seva and others, dimensional features of cellular phones such as width, height to width ratio, and size of navigation button are found good discriminating variables.

Physical Attributes	Cognitive Attributes
1. Weight	1. Ease of Use
2. Dimension	2. Learnability
3. Function Button Style	3. Image
4. Number buttons arrangement	3.1 Simplex–Complex
5. Screen Size	3.2 Handsome–Rustic
	3.3 Leisure–Formal

TABLE 2
Usability dimensions by usability questionnaires

Han *et al.*, 2000	Nielsen, 1993	ISO 9241-11
1. Perfromance Dimensions	1. Learnability	1. Effectiveness
1.1. Perception/Cognition	2. Efficiency	2. Efficiency
1.2. Memorization/Learnability	3. Errors	3. Satisfaction
1.3. Control/Action	4. Memorability	
2. Image/Impression Dimensions	5. Satisfaction	
2.1. Basic Sense		
2.2. Description of Image		
2.3. Evaluative Feeling		

SUMI	MPUQ
1. Affect	1. Ease of Learning and Use
2. Efficiency	2. Helpfullness and problem Solving
3. Control	3. Affective Aspect and Multimedia Properties
4. Helpfulness	4. Commands and Minimal Memory Load
5. Learnability	5. Control and Efficiency
	6. Typical Task for Mobile Phone

TABLE 3
Usability dimensions by usability questionnaires

Weights of the mobile phone are taken as a fuzzy attribute because the weight perception of the mobile phones differ from person to person, one expert to the other. It is important to take into account the weight perception rather than the weight itself. Other attributes which might be crisp such as dimension, screen size are also taken as fuzzy evaluations for the same reason.

As objective attributes; weight, dimension, and screen size are used and fuzzy scales are constructed for these attributes by taking into account a wide range of available mobile phones in the market. Then the weight, dimension and screen size characteristics of a particular alternative are fuzzified according to this scale constructed.

As subjective attributes, linguistic variables are function button style, number buttons arrangement, usability, learnability, appearance, fashionability, and perception are taken into account. They are evaluated by linguistic expressions (see Table 4). Fuzzy numbers used in this study are taken from Scale 4 given in Olcer and Odabasi [1].

4.2 Determination of Mobile Phone Alternatives

In order to determine an easy to use mobile phone, an analysis of the current models in the market is conducted. Then several selected models are compared according to their ergonomic design and properties. The models are classified

Criteria	Fuzzy Numbers				
Function Button Style	Very Regular (0,0,0.3)	Regular (0,0.25,0.5)	Medium (0.3,0.5, 0.7)	Irregular (0.5,0.75, 1)	Very Irregular (0.7,1, 1)
Number Buttons Arrangement	Very Regular (0,0,0.3)	Regular (0,0.25,0.5)	Medium (0.3,0.5, 0.7)	Irregular (0.5,0.75, 1)	Very Irregular (0.7,1, 1)
Usability	Very Low (0,0,0.3)	Low (0,0.25,0.5)	Medium (0.3,0.5, 0.7)	High (0.5,0.75, 1)	Very High (0.7,1, 1)
Learnability	Poor (0,0,0.3)	Fair (0,0.25,0.5)	Good (0.3,0.5, 0.7)	Very Good (0.5,0.75,1)	Excellent (0.7,1, 1)
Appearance	Very Simple (0,0,0.3)	Simple (0,0.25,0.5)	Moderate (0.3,0.5, 0.7)	Complex (0.5,0.75, 1)	Very Complex (0.7,1, 1)
Fashinonability	Very Rustic (0,0,0.3)	Rustic (0,0.25,0.5)	Moderate (0.3,0.5, 0.7)	Handsome (0.5,0.75, 1)	Very Handsome (0.7,1, 1)
Perception of Appearance	Very Formal (0,0,0.3)	Formal (0,0.25,0.5)	Moderate (0.3,0.5, 0.7)	Leisure (0.5,0.75, 1)	Very Leisure (0.7,1, 1)

TABLE 4
Linguistic terms and their corresponding fuzzy numbers

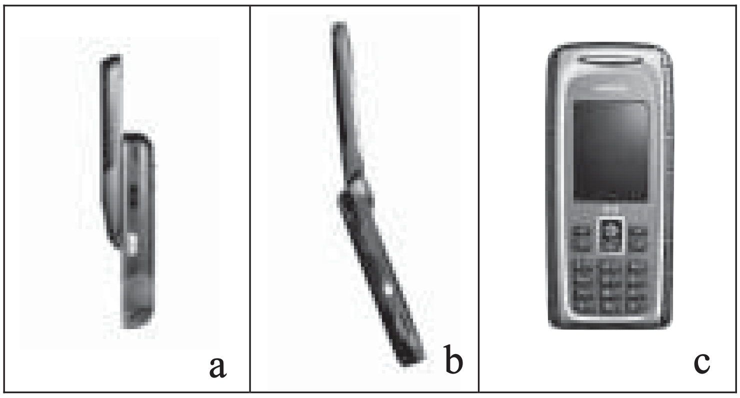

FIGURE 4
Alternative Mobile Phone Designs.

according to their physical characteristics (sliding, folding, and block) and then for each class two representative alternatives are selected regarding the retail price. The alternatives are approximately in the same price interval when the models are also classified according to their prices.

Six mobile phones of the same price range and having typical mobile phone functions are evaluated using Fuzzy AD. Two of the selected mobile phones are sliding type which is shown in Figure 4a, two of them are the folding type (Figure 4b) and the last two are block type (Figure 4c).

4.2.1 Experts' Evaluation of Mobile Phone Alternatives

Set of experts for each alternative are composed of three people. Two of them are Ergonomics' specialists, and one of them is the user of each mobile phone.

For tangible attributes, according to actual values of alternatives, the evaluation of alternatives are obtained directly, for intangible attributes, experts' opinions about the alternatives' designs are obtained by the linguistic variables. One advantage of using linguistic variables is that this kind of expression is more intuitive and easy for experts to give their opinions in an ambiguous situation where numerical estimations are hard to get. Experts' linguistic assessments for intangible attributes are transformed in to fuzzy numbers by using conversion scales which are mentioned in Subsection 4.1.1.

4.2.2 Aggregation of Experts' Evaluations

Step 1: After each expert opinion for each alternative is obtained and decision matrix for each expert is established, each trapezoidal fuzzy number is translated to standardized fuzzy number by dividing the values to the largest fuzzy number. The standardized fuzzy numbers for the first attribute are given in Table 5.

Step 2: Under each attribute, degree of agreement of the opinions between each pair of experts are E_i and E_j calculated by Table 1 Step 2. Similarity function values for the weight attribute are given in Table 5.

Step 3: Average degree of agreement of expert is calculated based on Table 1 Step 3.

Step 4: By dividing average degree of expert by sum of average degree of expert, the relative degree of expert is obtained using Table 1 Step 4.

Step 5: Since the importance of the experts are equal, β is taken 0, so the consensus degree coefficient value of each expert equals to values of its relative degree.

Step 6: The aggregation result of the fuzzy opinions are calculated using Table 1 Step 6.

Detailed aggregation calculations for the first attribute are given in Table 5. For each attribute, these aggregation calculations are done, and aggregated values of experts' opinions are obtained.

4.3 Selection of the Most Ergonomic Mobile Phone Design using Fuzzy AD

In the first step of Axiomatic Design, Functional Requirements (FRs) which shows the minimum set of independent requirements that characterize the design goals called are decided. In the second step, System Ranges (system capable ranges) are decided by experts. We have already done these two steps in the previous stage of the model.

	P1	P2	P3	P4	P5	P6
e1	(0.06, 0.18, 0.29)	(0.24, 0.41, 0.59)	(0.06, 0.18, 0.29)	(0.06, 0.18, 0.29)	(0.06, 0.18, 0.29)	(0.24, 0.41, 0.59)
e2	(0.06, 0.18, 0.29)	(0.24, 0.41, 0.59)	(0.24, 0.41, 0.59)	(0.06, 0.18, 0.29)	(0.24, 0.41, 0.59)	(0.24, 0.41, 0.59)
e3	(0.06, 0.18, 0.29)	(0.06, 0.18, 0.29)	(0.06, 0.18, 0.29)	(0.06, 0.18, 0.29)	(0.24, 0.41, 0.59)	(0.24, 0.41, 0.59)
Degree of Agreement(S)						
S12	1.00	1.00	0.77	1.00	0.77	1.00
S13	1.00	0.77	1.00	1.00	0.77	1.00
S23	1.00	0.77	0.77	1.00	1.00	1.00
Average Degree of Agreement(AA)						
AA(E1)	1.00	0.88	0.88	1.00	0.77	1.00
AA(E2)	1.00	0.88	0.77	1.00	0.88	1.00
AA(E3)	1.00	0.77	0.88	1.00	0.88	1.00
Relative Degree of Agreement(RA)						
RA(E1)	0.33	0.35	0.35	0.33	0.30	0.33
RA(E2)	0.33	0.35	0.30	0.33	0.35	0.33
RA(E3)	0.33	0.30	0.35	0.33	0.35	0.33
RA(HM)	(0.06, 0.18, 0.29)	(0.19, 0.34,0.50)	(0.11, 0.25, 0.38)	(0.06, 0.18, 0.29)	(0.19, 0.34,0.50)	(0.24, 0.41, 0.59)

TABLE 5
Aggregation of Under the first attribute

In the third step Design Ranges (design tolerance ranges) are decided, so the FRs that should be satisfied in a Mobile Phone are given below:

FR1 = Weight must be light,
FR2 = Dimension must be medium,
FR3 = Screen Size must be large,
FR4 = Function Button Style must be moderate,
FR5 = Number buttons arrangement must be irregular,
FR6 = Usability must be high,
FR7 = Learnability must be very good,
FR8 = Appearance must be moderate,
FR9 = Fashionability must be handsome,
FR10 = Perception of appearance must be moderate.

In the fourth step, Common Range, the intersection area between design range and system range is calculated by the following formula:

When $M_1 = (l_1, m_1, n_1)$ and $M_2 = (l_2, m_2, n_2)$, and when $l_1 \leq u_2$, the d is the ordinate of the highest point D between M_1 and M_2, and it is calculated according to the following formula [24]: $\mu(d) = \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}$ and when $l_1 > u_2$, μ (d) is zero [25].

In the fourth step, for each FR^i the probability of achieving the FR^i is calculated as follows:

$$p^i = \left(\frac{Common\ Range}{System\ Range} \right)$$

In the sixth step, for each FR^i the Information Content is calculated by the following formula:

$$I^i = \log_2 \left(\frac{1}{p^i} \right)$$

In the last step, total Information Content is calculated, and the alternative with the minimum information content is chosen. All of the information contents are listed in the Table 6. According to Table 5, the phone with minimum information content is P1. As the alternative with minimum information content is best, P1 which is a sliding one is selected as the most ergonomic mobile phone together for physical and mental attributes. Also, for one of the two main attributes, physical aspects, P3 which is a folding one is the best, on the other hand for cognitive approach P1 is found the best.

5 CONCLUSIONS AND FURTHER SUGGESTIONS

In this paper, fuzzy multi-attribute axiomatic design approaches for selection of the most ergonomic electronic consumer product is introduced and the implementation process is represented by mobile phone selection as a real world example.

	FR1	FR2	FR3	FR4	FR5	Phy. Total	FR6	FR7	FR8	FR9	FR10	Cog. Total	Total
p1	0	1.93	0	1.35	0.5	3.78	0	0.51	3.51	0	1.35	5.37	9.15
p2	2.58	1.93	0	1.38	1.35	7.24	0	2.5	8.75	5.2	2.1	18.55	25.79
p3	0.83	0	2.3	1.38	0.5	5.01	0	6.1	3.26	5.2	1.35	15.91	20.92
p4	0	3.55	0	2.17	3.26	8.98	0	2.5	2.17	2.5	0	7.17	16.15
p5	2.58	2	0	5.73	3.26	13.57	0	0.12	5.74	3.56	3.26	12.68	26.25
p6	4.69	2	0	2.17	0.54	9.4	inf	2.5	8.75	5.2	3.31	inf	inf

TABLE 6
Information Content for Alternatives

Fuzzy axiomatic design method rather than Crisp AD is used because of the fuzzy nature of the problem. For the situations where complete information can be obtained, Crisp AD will be sufficient to solve the decision model. According to Ross [26], the aim should be matching the model type with the character of the uncertainty exhibited in the problem. According to uncertainty level, three different types of model can be used. If a system has a little uncertainty, closed-form mathematical expression would be the suitable method. For systems which have more uncertainty, but for which significant data exist, model-free method should be used. However, with the systems which have incomplete information, non-obtainable information or unquantifiable information, fuzzy modeling provides a way to understand system [26].

The models were selected as representative of the group they belong in terms of dimensions, design and price level. The price is taken into account because the higher is the price of the phone; the larger is its screen size and dimensions. To overcome the price effect on design, the selected types are different in terms of design (folding, sliding, and block) but close in terms of dimension and they belong to the same price level. Independent of the price, it can be said that these results would apply for phones of similar dimensions. For extremely different designs, the analysis should be conducted from the beginning. One advantage of the proposed analysis is that it can be applied to any electronic consumer product group to determine the most ergonomic design among the selected alternatives, since it takes into account both physical and cognitive aspects of ergonomic design.

In our case, ergonomic mobile phone selection has too many attributes and these attributes about the problem are generally conflicting with each other and measured in different scales. Also, it is difficult to measure the intangible criterion quantitatively. Therefore, in this study fuzzy AD method is used.

As a result, P1 (sliding type) is found most ergonomic mobile phone according to both physical and cognitive approaches. Also, according to physical approach P3 (folding type) is the best. However, according to cognitive approach P1 is found the best. The AD method for the selection process has advantages more than other multi-attribute decision making methods. Firstly, the designer wants to satisfy a criterion peak pressure but may not want to meet this criterion at the best level. This is not possible when working with other existing models like AHP, fuzzy AHP, and scoring models. Also, the AD method rejects an alternative which does not meet the decision range of any criterion, and the other methods do not. The proposed methodology can be used for competing electronic mobile products in the end-user market. Also, alternatives of prototypes can be evaluated during development process. Moreover, dimensions of ergonomic mobile phones can help develop ergonomic mobile phones.

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