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Design of Light-emitting Diode Device Considering Sensor Technology Using Analytical Hierarchical Procedure

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Rapid technological and economic development has created intense competition in today's consumer market. Thus, design is playing a more important role in product development than before, especially in the development of electronic devices. In the design of a new electronic device, the use of light-emitting diode (LED) and sensors has become increasingly inevitable. However, it is not easy to evaluate the design of a product from the viewpoints of both consumers and developers or manufacturers. Therefore, using the analytical hierarchical process (AHP) and fuzzy evaluation method and taking an LED device with a fan as an example, we determined the important criteria and factors in designing a new product. The criteria and factors were defined through interviews and a questionnaire survey with 14 experts. As a result, 24 factors were found to affect the five criteria of function, efficiency, aesthetics, creativity, and economy. The AHP and fuzzy evaluation results indicated efficiency to be the most important criterion and the fan air volume of the LED device the most critical factor in the design. Convenience, product texture, innovation, and product packaging were also found to be important in designing the LED device. The results of this study may be a reference for developing new products with sensors and LEDs.

1. Introduction

As consumers require diverse functions and designs for products, a monotonous product no longer satisfies consumers' demands. To compete in the market, companies try to release products with fancy designs and convenient functionalities, which influence decision-making for developing new products. Selecting designs for products is not easy as it requires various evaluation criteria considering consumers' preferences and technological challenges. These criteria are often complex and wide-ranged and diverse factors must be considered. The product design is divided into a single-product design or a family-product design depending on the

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design's objective and the product's marketability. Electronic components have become miniaturized with more functionality with the development of technology and allow more attractive product designs. However, miniaturized components face the problem of high heat generation per unit area, which affects the operation of the electronic product. Therefore, excess heat must be dissipated from the components by incorporating an effective cooling system.

Recently, using sensors in product design has become more popular in order to enable more creative, interactive, and customized electronic devices to be produced and to solve the heat problem. Sensors are also used in products to improve users' experience and provide emotional feelings by allowing the products to respond to users' preferences in vision, sound, and touch.(1) An example of using sensors in electronic devices is the light-emitting diode (LED) device. The LED is a semiconductor device that emits infrared or visible light upon applying current. It displays different colors depending on the materials and the energy used for lighting. LEDs are commonly used for lamps (lights) and displays with sensors and are also used as sensors for various other purposes. The LED device is often implemented with motion and light sensors to emit light in accordance with the movement and light in its ambient surroundings. By reversing its polarity and using the current generated by incident light, LEDs are used as a sensor that measures the color and intensity of light.(2)

Although the LED device can have diverse designs and functions depending on their purpose of use, it is still important to determine the important design elements for successful marketing. Therefore, in this study, we constructed an evaluation framework for the product design of an LED device based on a multicriteria decision-making method and fuzzy theory. The purpose is to select appropriate product design concepts to reduce the uncertainty and ambiguity in design selections. In the case of the LED device for displaying text, we applied the weighting coefficient method and the analytical hierarchical procedure (AHP) method to effectively understand the important attributes, advantages, and disadvantages of using sensors in product design.

2. Research Methods

We used the fuzzy evaluation method as the research method for the design of the fan with an LED text display. AHP was also used to determine relative weights and evaluation factors.(3,4)

2.1 AHP

AHP was first proposed by Saaty in 1980 for developing a decision-making process with multiple goals.(5) Hsiao pointed out that the hierarchical structure is important to explore the interaction between various criteria in the hierarchy and their impacts on the decision-making structure.(6) AHP simplifies complex systems to a concise elemental hierarchy system by using pairwise comparisons between criteria at each level. Then, the pairwise comparison matrix is used to obtain the eigenvector of the matrix at each level, representing the priority of each criterion.(7,8) The pairwise comparison matrix is used as an indicator for decision-making or evaluation. The process of obtaining a pairwise comparison matrix includes the following steps: (1) problem analysis and listing of evaluation factors, (2) construction of a hierarchical structure,

(3) establishment of a dual matrix, (4) determination of eigenvalues and eigenvectors, (5) verification of duality consistency of the matrix, and (6) calculation of the dominance ratio of each factor.[9–12]

To define the design elements of the LED text display fan, semistructured interviews with experts in relevant industries were carried out.[13–18] The goal of AHP analysis in this study was to choose the best design among the four different designs (alternatives) proposed in this study. The design elements were reflected in the criteria and factors decided on the basis of the results of the expert interview and questionnaire survey. Factors that affected the criteria were found to establish a hierarchical structure. In this study, the degrees of influence of those factors were quantified first by 14 experts, including 10 designers and 4 workers. From the questionnaire survey results, the relative weight of each criterion was obtained. The questionnaire was validated for its internal consistency.

2.2 Fuzzy evaluation method

In the fuzzy evaluation method, related factors and their evaluations are considered[19–21] and the following procedure is carried out: (1) determine the influencing factor set, (2) determine the factor weight set, (3) determine the parameter evaluation set, (4) establish the factor evaluation matrix, (5) carry out the fuzzy evaluation, and (6) process the evaluation index.[22,23] The purpose of the fuzzy evaluation is to obtain an optimal evaluation result from the evaluation set taking into consideration the influencing factors. The weight of the factor is determined by the weighting coefficient method, AHP, or the paired comparison method. Regardless of the method used to determine the weight, human factors such as perception, preference, and judgment[24] are always involved.

The evaluation set is a collection of various evaluations made by the evaluator regarding the object. In this study, the evaluation set is defined as V ={strongly agree, agree, neutral, disagree, strongly disagree}. The single-factor fuzzy evaluation determines the degree of the evaluation of a single element in the set. With the ith factor U_i, element j in the evaluation set is defined as r_{ij}, and the evaluation result of element i is represented as U_i. In the fuzzy sets,

$$\tilde{R}_i = \frac{r_{i1}}{v_1} + \frac{r_{i2}}{v_2} + \ldots + \frac{r_{in}}{v_n} = \left(r_{i1}, r_{i2}, \ldots, r_{in}\right), \tag{1}$$

where $\tilde{R}_i$ =(r_{i1}, r_{i2},…,r_{in}) is the single-factor evaluation set, which is a fuzzy set. Similarly, the single-factor evaluation set corresponding to each factor is obtained as follows.

$$\begin{aligned} \widetilde{R}_1 &= (r_{11}, r_{12}, \cdots, r_{1n}) \\ \widetilde{R}_2 &= (r_{21}, r_{22}, \cdots, r_{2n}) \\ &\vdots \\ \widetilde{R}_m &= (r_{m1}, r_{m2}, \cdots, r_{mn}) \end{aligned} \tag{2}$$

A fuzzy matrix consisting of membership degrees for each single-factor evaluation set is as follows.[25]

$$\tilde{R} = (r_{ij})_{m\times n} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{3}$$

In this study, a multilevel fuzzy comprehensive evaluation was adopted and carried out as in complex choices, where many factors must be considered and factors exist at several levels.[26–28]

The fuzzy evaluation matrix of a certain evaluation target is shown in Eq. (4), in which a weight is considered. Then, the fuzzy matrix is

$$\widetilde{B} = \widetilde{W} \bullet \widetilde{R} = (b_1, b_2, \cdots b_j, \cdots b_n)\,, \tag{4}$$

where the symbol "•" represents the fuzzy synthesis operation. There are several synthesis methods when using the weighted fuzzy matrix $\tilde{W}$ and $\tilde{R}_i$ as follows.

Method 1[29]

$$b_j = \overset{i=1}{\underset{m}{\vee}} \left(w_i \wedge r_{ij} \right); j = 1, 2, \ldots, n \tag{5}$$

As all $r_{ij} > w_{ij}$ are not considered, when factors normalized with weights are small, single-factor evaluation information may be lost. When there are few factors, w_{ij} becomes large, so $w_{ij} > r_{ij}$ is considered.

Method 2

$$b_j = \overset{i=1}{\underset{m}{\vee}} \left(w_i r_{ij} \right); j = 1, 2, \ldots, n \tag{6}$$

In this method, multiplication is performed so as to not lose any useful information. However, the operation "∨" still may lose useful information.

Method 3

$$b_j = \min\{1, \sum_{i=1}^{m} \left(w_i \wedge r_{ij} \right)\}; j = 1, 2, \ldots, n \tag{7}$$

In this method, valuable information still can be lost because of large r_{ij} and w_{ij}, and b_j may reach the upper limit. When the values of r_{ij} and w_{ij} are small, b_j may be equal to the sum of w_i, so the expected evaluation result cannot be obtained.[4]

Method 4

$$b_j = \min\{1, \sum_{i=1}^{m} w_i r_{ij}\}; j = 1,2,...,n \tag{8}$$

This method is characterized by the fact that when w_i is normalized,

$$\sum_{i=1}^{m} w_i = 1, \sum_{i=1}^{m} w_i r_{ij} << 1, \tag{9}$$

and then,

$$b_j = \sum_{i=1}^{m} w_i r_{ij}; j = 1,2,...,n; \sum_{i=1}^{m} w_i = 1\,. \tag{10}$$

In this method, the influence of all factors retains all the information of single-factor judgments. There is no upper limit on w_i and r_{ij}, and only w_i needs to be normalized.[30]

As models 1, 2, and 3 have certain constraints and require extreme conditions, there is a loss of information in the evaluation.[31] Thus, we used method 4. After obtaining the evaluation index b_j (j =1,2,…,n), the evaluation result was obtained by the maximum membership method and the weighted average method.[32]

3. Results and Discussion

From the interview and questionnaire survey, we obtained five criteria and twenty-four factors affecting them. The criteria were defined as functions (U_1), efficiency (U_2), aesthetics (U_3), creativity (U_4), and economy (U_5). The factors affecting each criterion were found to be U_1={convenience (u_{11}), unified form and function (u_{12})}; U_2={power saving (u_{21}), noise level (u_{22}), fan air volume (u_{23}), LED text change (u_{24})}; U_3={product texture (u_{31}), the color of appearance (u_{32}), change in appearance (u_{33}), change in LED brightness (u_{34})}; U_4={innovation (u_{41}), uniqueness (u_{42}), avant-garde (u_{43}), personal style (u_{44})}; and U_5={product material (u_{51}), assembly method (u_{52}), product packaging (u_{53}), wire length (u_{54}), cost estimate (u_{55})}.

For the importance of each factor, the relative weight of each factor and the weight ratio between factors were determined. Table 1 shows the weights of the criteria for selecting the

Table 1
Weights of criteria of LED device design.

Sequence	Criteria	Weights	Consistency ratio
1	Function (U_1)	0.078	
2	Efficiency (U_2)	0.400	
3	Aesthetics (U_3)	0.120	0.05
4	Creativity (U_4)	0.243	
5	Economy (U_5)	0.159	

design element of LED devices. Among the five criteria, efficiency had the highest weight of 0.4, followed by creativity (0.243), economy (in manufacturing) (0.159), aesthetics (0.120), and functions (0.078).

Table 2 lists the weights of the factors affecting the criteria. The important factors for each criterion were convenience for function, fan air volume for efficiency, product texture for aesthetics, innovation for creativity, and product packaging for economy. The consistency ratios of the criteria and factors were less than 0.05, and the overall level consistency was 0.028, which implied that the questionnaire survey had significant consistency and that the assessment of the entire hierarchy was acceptable.

According to the above research results, the following weight matrices of each factor were obtained.

$$\begin{aligned}
\tilde{W}_1 &= [0.667, 0.333] \\
\tilde{W}_2 &= [0.09, 0.22, 0.592, 0.099] \\
\tilde{W}_3 &= [0.281, 0.239, 0.140, 0.34] \\
\tilde{W}_4 &= [0.418, 0.12, 0.191, 0.271] \\
\tilde{W}_5 &= [0.229, 0.079, 0.298, 0.238, 0.156] \\
\tilde{W}_6 &= [0.078, 0.40, 0.120, 0.243, 0.159]
\end{aligned} \tag{11}$$

Table 2
Weight of factors of criteria in LED device design.

Criteria	Factor	Weight	Consistency ratio
Function (U_1)	Convenience (u_{11})	0.667	0.01
	Unified form and function (u_{12})	0.333	
Efficiency (U_2)	Power saving (u_{21})	0.09	0.01
	Noise level (u_{22})	0.22	
	Fan air volume (u_{23})	0.592	
	LED text change (u_{24})	0.099	
Aesthetics (U_3)	Product texture (u_{31})	0.281	0.02
	Appearance Color (u_{32})	0.239	
	Changes in appearance (u_{33})	0.140	
	LED brightness change (u_{34})	0.34	
Creativity (U_4)	Innovation (u_{41})	0.418	0.03
	Uniqueness (u_{42})	0.12	
	Avant-garde (u_{43})	0.191	
	Personal style (u_{44})	0.271	
Economy (U_5)	Product material (u_{51})	0.229	0.05
	Assembly method (u_{52})	0.079	
	Product packaging (u_{53})	0.298	
	Wire length (u_{54})	0.238	
	Cost estimate (u_{55})	0.156	

Then, the following evaluation sets of each factor were established.

$$\tilde{R}_1 = \begin{bmatrix} 0.32 & 0.48 & 0.16 & 0.04 & 0.00 \\ 0.19 & 0.29 & 0.48 & 0.05 & 0.00 \end{bmatrix}$$

$$\tilde{R}_2 = \begin{bmatrix} 0.33 & 0.38 & 0.25 & 0.04 & 0.00 \\ 0.20 & 0.30 & 0.40 & 0.10 & 0.00 \\ 0.46 & 0.23 & 0.31 & 0.00 & 0.00 \\ 0.35 & 0.26 & 0.35 & 0.04 & 0.00 \end{bmatrix}$$

$$\tilde{R}_3 = \begin{bmatrix} 0.20 & 0.30 & 0.40 & 0.10 & 0.00 \\ 0.21 & 0.16 & 0.53 & 0.11 & 0.00 \\ 0.21 & 0.32 & 0.32 & 0.16 & 0.00 \\ 0.35 & 0.39 & 0.17 & 0.09 & 0.00 \end{bmatrix} \quad (12)$$

$$\tilde{R}_4 = \begin{bmatrix} 0.18 & 0.41 & 0.36 & 0.05 & 0.00 \\ 0.19 & 0.43 & 0.29 & 0.10 & 0.00 \\ 0.35 & 0.39 & 0.17 & 0.09 & 0.00 \\ 0.21 & 0.47 & 0.11 & 0.21 & 0.00 \end{bmatrix}$$

$$\tilde{R}_5 = \begin{bmatrix} 0.33 & 0.50 & 0.08 & 0.08 & 0.00 \\ 0.18 & 0.41 & 0.36 & 0.05 & 0.00 \\ 0.33 & 0.38 & 0.25 & 0.04 & 0.00 \\ 0.21 & 0.32 & 0.32 & 0.16 & 0.00 \\ 0.38 & 0.29 & 0.19 & 0.14 & 0.00 \end{bmatrix}$$

Next, each product of the fuzzy evaluation matrix was calculated as follows on the basis of the above matrices.

$$\begin{array}{ll} \text{Functional factors} & \tilde{B}_1 = \tilde{W}_1 \bullet \tilde{R}_1 = \begin{bmatrix} 0.29 & 0.44 & 0.22 & 0.03 & 0.00 \end{bmatrix} \\ \text{Efficacy factor} & \tilde{B}_2 = \tilde{W}_2 \bullet \tilde{R}_2 = \begin{bmatrix} 0.44 & 0.22 & 0.29 & 0.03 & 0.00 \end{bmatrix} \\ \text{Aesthetic factors} & \tilde{B}_3 = \tilde{W}_3 \bullet \tilde{R}_3 = \begin{bmatrix} 0.29 & 0.32 & 0.31 & 0.07 & 0.00 \end{bmatrix} \\ \text{Creativity factor} & \tilde{B}_4 = \tilde{W}_4 \bullet \tilde{R}_4 = \begin{bmatrix} 0.16 & 0.37 & 0.33 & 0.12 & 0.00 \end{bmatrix} \\ \text{Economic factors} & \tilde{B}_5 = \tilde{W}_5 \bullet \tilde{R}_5 = \begin{bmatrix} 0.30 & 0.34 & 0.23 & 0.11 & 0.00 \end{bmatrix} \end{array} \quad (13)$$

The products were used in the criteria evaluation matrix, and the final fuzzy evaluation matrix was obtained as

$$\tilde{R}^* = \begin{bmatrix} \tilde{B}_1 \\ \tilde{B}_2 \\ \tilde{B}_3 \\ \tilde{B}_4 \\ \tilde{B}_5 \end{bmatrix} = \begin{bmatrix} 0.29 & 0.44 & 0.22 & 0.03 & 0.00 \\ 0.44 & 0.22 & 0.29 & 0.03 & 0.00 \\ 0.29 & 0.32 & 0.30 & 0.07 & 0.00 \\ 0.16 & 0.37 & 0.33 & 0.12 & 0.00 \\ 0.30 & 0.34 & 0.23 & 0.11 & 0.00 \end{bmatrix}. \tag{14}$$

In the fuzzy evaluation matrix, the maximum membership method and the weighted average method are used frequently. The weighted average method converts fuzzy values into numerical values through defuzzification. The purpose of defuzzification is to convert data of a fuzzy nature into explicit numbers, that is, fuzzy numbers. We applied the rank assignment based on the weighted average method. By applying V={strongly agree, agree, neutral, disagree, strongly disagree}={1, 0.75, 0.50, 0.25, 0} to the calculation of the defuzzified evaluation, the results shown in Table 3 were obtained.

The above results indicated that all criteria except creativity were acceptable for deciding the important design elements of the LED device since the sums of the defuzzified values of ‘strongly agree’ and ‘agree’ were larger than 0.60. Efficiency showed a defuzzified value of 0.44 and had the highest weight of 0.400 among the criteria. This implies that the experts put the highest priority on the efficiency of the LED device. For other criteria, convenience, product texture, innovation, and product packaging were important factors.

As examples of alternative AHP in this study, we designed four different types of LED device, as shown in Table 4. The first device (device 1) had an oriental design comprising small squares on the front of an air outlet, which induces a simple, calm, and restrained feeling. In the second device (device 2), a four-petal flower shape was adopted. The petals formed a cross-shaped corolla. The third device (device 3) has a bubble ball design on the air outlet. The fourth device (device 4) has a honeycomb design to optimize the structural strength. In designing the device, the target flow rate was larger than 6 CFM at 2000 RPM and static pressure was higher than 1.74 mm-H_2O.

We simulated the four different designs shown in Table 5, each of which had a different fan (impeller) shape and guard of the fan. The numerical analysis was conducted to observe the changes in the flow field and the performance of the four different types of fan. The turbulence was calculated to be the largest for device 3 with the bubble ball design. The impact of the airflow streamlines was the lowest for design 4 with the honeycomb design.

Table 3
Defuzzified value of each factor.

Criteria	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Defuzzification
Function	0.29	0.44	0.22	0.03	0.0	0.75
Efficiency	0.44	0.22	0.29	0.03	0.00	0.76
Aesthetics	0.29	0.32	0.09	0.07	0.00	0.70
Creativity	0.16	0.37	0.33	0.12	0.00	0.64
Economy	0.30	0.34	0.23	0.11	0.03	0.70

Table 4
(Color Online) LED devices with different designs.

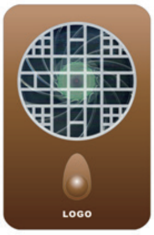
No.	Device	Design concept	Description
1		Oriental style	A simple, calm, and restrained style was presented, and it has an original and rustic flavor of the Orient.
2		Four-petal flower	The four petals form a cruciform corolla with a meshwork that divides the interior into four groups of stomata, similar in structure to the body of petals.
3		Bubble ball	Bubble balls are used as the main body of the design, but also increase porosity.
4		Honeycomb	The honeycomb is a multi-structured mesh, and this structure is the best for achieving high structural strength and wind resistance.

Table 5
(Color online) Results of design and airflow simulations of the four devices.

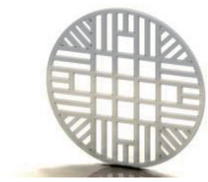
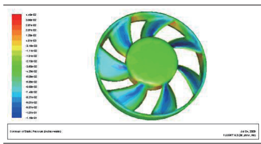
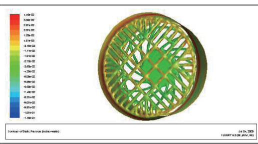
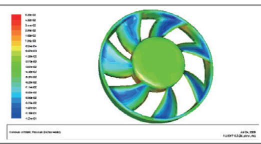
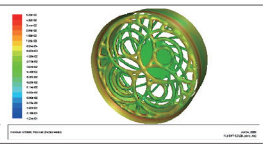
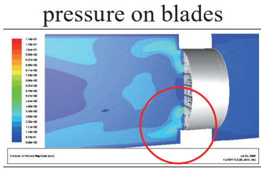
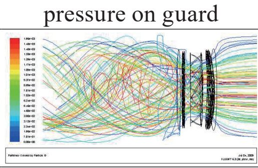
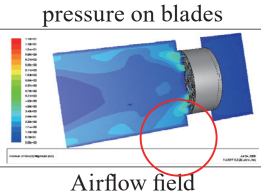
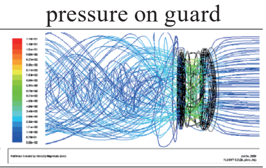
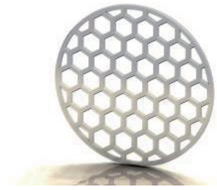
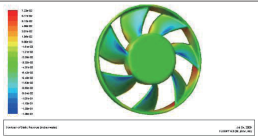
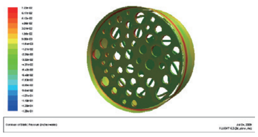
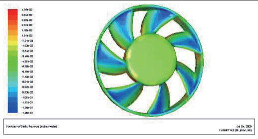
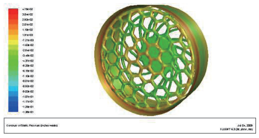
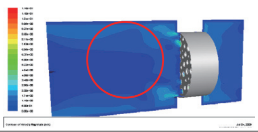
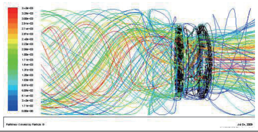
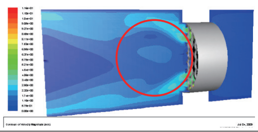
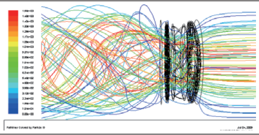
 Device 1		 Device 2	
			
Distribution of air pressure on blades	Distribution of air pressure on guard	Distribution of air pressure on blades	Distribution of air pressure on guard
			
Airflow field	Airflow streamline	Airflow field	Airflow streamline

Table 5
(Continued)

			
Device 3		Device 4	
			
Distribution of air pressure on blades	Distribution of air pressure on guard	Distribution of air pressure on blades	Distribution of air pressure on guard
			
Airflow field	Airflow streamline	Airflow field	Airflow streamline

The flow field in devices 1 and 3 varied greatly owing to counterflows and vortices caused by the numerous squares and bubble balls. The smoothness of the fan shape affected the air flow through the blades and the vortex between the blades and the outlet. At the highest flow velocity, the velocity field of device 4 seems to be smoother than those of the other devices. It was observed that the flow from the outlet was largely affected by the outlet shape.

Table 6 shows the selected optimal designs of the LED device using AHP and the fuzzy evaluation method. Device 4 showed the highest defuzzified value with a sum of 0.50 for satisfaction, followed by device 1 (0.43), device 2 (0.42), and device 3 (0.39).

The selection index was calculated using Eq. (15). The result in Table 7 shows that the experts agreed that device 4 was the most appropriate device considering the criteria of function, efficiency, aesthetics, creativity, and economy and the factors affecting the criteria.

Table 6
(Color Online) Final results obtained by AHP and fuzzy evaluation method and used to select the optimal design of the LED device.

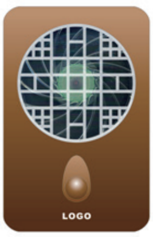
Design case 1	Very satisfied	Satisfied	Neutral	Dissatisfied	Very dissatisfied	Defuzzy value
	0.19	0.24	0.19	0.19	0.19	0.51

Table 6
(Continued)

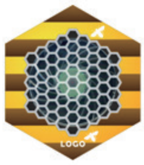
Design case 1	Very satisfied	Satisfied	Neutral	Dissatisfied	Very dissatisfied	Defuzzy value
	0.19	0.23	0.19	0.19	0.19	0.5
	0.17	0.22	0.17	0.22	0.22	0.48
	0.25	0.25	0.25	0.22	0.03	0.62

Table 7
Selection indices of device 4.

Selected design	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Defuzzification
	0.42	0.21	0.28	0.07	0.00	0.748

$$\tilde{C} = \tilde{W} \bullet \tilde{R}_2 = \begin{bmatrix} 0.42 & 0.21 & 0.28 & 0.07 & 0.00 \end{bmatrix} \tag{15}$$

4. Conclusions

Competition in the electronic device market has become vigorous owing to technological and economic development. Thus, it is important to present appealing designs to attract consumers' interest. In the design of electronic devices, LEDs and sensors play an important role in providing aesthetic satisfaction and functionality. In this study, we determined the important criteria and factors in designing new products. The criteria and factors were defined through interviews and a questionnaire survey with 14 experts. As a result, five criteria were identified: function, efficiency, aesthetics, creativity, and economy. Also, 24 factors were identified: convenience, unified form, and function for function; power saving, noise level, fan air volume, and LED text change for efficiency; product texture, appearance color, appearance change, and LED brightness change for aesthetics; innovation, uniqueness, avant-garde, and personal style for creativity; and product material, assembly method, product packaging, wire length, and cost estimate for economy. The results of AHP and fuzzy evaluation showed that efficiency was the most important criterion, and the fan air volume of the LED device was the critical factor in the design. Creativity, economy, aesthetics, and functions were considered important criteria in choosing the optimal design in the order of the AHP weight. Convenience, product texture, innovation, and product packaging were selected as the most influential factors. Among the proposed four devices with different designs, device 4 with the honeycomb design was chosen because it had the highest defuzzified value as its air flow rate was the largest and because of its appearance.

The LED devices on the market have various designs and functions depending on their purpose of use. By using the research framework of this study, appropriate product design concepts can be chosen by determining the necessary attributes, advantages, and disadvantages. From this perspective, the functionality of sensors and related technology should be included in product design to improve users' experiences and provide satisfaction. As revealed in this study, consumers are concerned about efficiency, convenience, and innovation, which can be improved by using appropriate sensor technology. Therefore, the method used in and the results of this study are expected to be a reference for creating designs of electronic devices with sensors.

References

1 The Ultimate Experience: A Guide to the Principles of Sensory Design: https://www.toptal.com/designers/ux/sensory-design (accessed March 2023).
2 Activity: LED as Light Sensor: https://wiki.analog.com/university/courses/electronics/electronics-lab-led-sensor (accessed March 2023).
3 S. Liu, J. Zhang, W. Liu, and Y. Qian: Energy Procedia **14** (2012) 937. https://doi.org/10.1016/j.egypro.2011.12.1036
4 J. Peng: Energy Procedia **17** (2012) 595. https://doi.org/10.1016/j.egypro.2012.02.141
5 T. L. Saaty: The Analytic Hierarchy Process (New York, McGraw-Hill, 1980).
6 S.-W. Hsiao: Int. J. Ind. Ergon. **29** (2002) 41. https://doi.org/10.1016/S0169-8141(01)00048-8
7 S. Bortot, P. Marques, and A. M. P. Ricardo: DISA Working Papers (2011). https://ideas.repec.org/p/trt/disawp/2011-06.html (accesed March 2023).
8 A. Gorener, K. Toker, and K. Ulucay: Procedia Soc. Behav. Sci. **58** (2012) 1525. https://doi.org/10.1016/j.sbspro.2012.09.1139
9 F. D. Felice and A. Petrillo: Procedia Soc. Behav. Sci. **5** (2012) 1555. https://doi.org/10.1016/j.sbspro.2012.09.1142
10 A. Suner, C. C. Celikoglu, D. Dicle, and S. Sokmen: Artif. Intell. **56** (2012) 59. https://doi.org/10.1016/j.artmed.2012.05.003
11 J. M. Bradley, S. Madge, A. M. Morton, A. L. Quittner, and J. S. Elborn: J. Cyst. Fibros. **11** (2012) 387. https://doi.org/10.1016/j.jcf.2012.03.004.
12 N. Subramanian and R. Ramanathan: Int. J. Prod. Econ. **138** (2012) 215. https://doi.org/10.1016/j.ijpe.2012.03.036
13 M. B. Javanbarg, C. Scawthorn, J. Kiyono, and B. Shahbodaghkhan: Expert Syst. Appl. **39** (2012) 960. https://doi.org/10.1016/j.eswa.2011.07.095
14 J. I. Luebke and J. M. Amatrudo: Neurobiol. Aging **33** (2012) 1085. https://doi.org/10.1016/j.neurobiolaging.2010.07.002
15 R. Schulz, T. Kirschstein, H. Brehme, K. Porath, U. Mikkat, and R. Kohling: Neurobiol. Dis. **45** (2012) 337. https://doi.org/10.1016/j.nbd.2011.08.019
16 A. Dario, H. O. Sicim, and E. Balikci: J. Cryst. Growth **337** (2011) 65. https://doi.org/10.1016/j.jcrysgro.2011.09.057
17 L. Xu: Phys. Procedia **33** (2012) 1924. https://doi.org/10.1016/j.phpro.2012.05.304
18 M. Bernasconi, C. Choirat, and S. Seri: J. Math. Psychol. **55** (2011) 152. https://doi.org/10.1016/j.jmp.2010.11.002
19 Z. Zhang: Inf. Sci. **219** (2013) 124. https://doi.org/10.1016/j.ins.2012.07.013

20 D. Ghosh and D. Chakraborty: Fuzzy Sets Syst. **209** (2012) 66. https://doi.org/10.1016/j.fss.2012.02.011
21 M. A. Basaran: Appl. Soft Comput. **12** (2012) 1810. https://doi.org/10.1016/j.asoc.2012.01.005
22 R. E. Bellman and L. A. Zadeh: Manag. Sci. **17** (1970) 141 https://doi.org/10.1287/mnsc.17.4.B141
23 S.-W. Hsiao and H.-C. Tsai: Int. J. Ind. Ergon. **35** (2005) 411. https://doi.org/10.1016/j.ergon.2004.10.007
24 S.-W Hsiao: Int. J. Ind. Ergon. **21** (1998) 103. https://doi.org/10.1016/S0169-8141(96)00072-8
25 Y.-F. Kuo and P.-C. Chen: Expert Syst. Appl. **30** (2006) 612. https://doi.org/10.1016/j.eswa.2005.07.007
26 S.-M. Chen and Y.-C. Chang: Expert Syst. Appl. **38** (2011) 12202. https://doi.org/10.1016/j.eswa.2011.03.084
27 J. Chachi and S. M. Taheri: Expert Syst. Appl. **38** (2011) 5240. - https://doi.org/10.1016/j.eswa.2010.10.034
28 S. Sadi-Nezhad and K. K. Damghani: Appl. Soft Comput. **10** (2010) 1028. - https://doi.org/10.1016/j.asoc.2009.08.036
29 H.-C. Tsai and S.-W. Hsiao: Inf. Sci. **158** (2004) 233. https://doi.org/10.1016/j.ins.2003.08.001
30 J. Hurault, S. Kouidri, F. Bakir, and R. Rey: Flow Meas. Instrum. **21** (2010) 155. https://doi.org/10.1016/j.flowmeasinst.2010.02.003
31 S.-H. Tsaur, R.-Y. Chang, and C.-H. Yen: Tour. Manag. **23** (2002) 107. https://doi.org/10.1016/S0261-5177(01)00050-4
32 M.-J.J. Wang and T.-C. Chang: Fuzzy Sets Syst. **72** (1995) 263. https://doi.org/10.1016/0165-0114(94)00289-J

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