A Study of the Evaluation of Products by Industrial Design Students

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ABSTRACT

The objective of this study is to provide industrial design students with a comprehensive approach of product evaluation during the course of a research project. During the design evaluation stage, a student often encounters vague information since the attributes of product design demands are usually not quantifiable. Therefore, one of the important topics during the product development processes is to allow a student to carry out design evaluations effectively. The fuzzy Analytic Hierarchy Process (AHP) was utilized in this study to assess product designs and resolve the problems that might occur during product assessments. The purposive sampling technique was used in the questionnaire survey. By assigning a weighted value to each of the evaluation criteria, the case study verified the feasibility of the proposed design approach in fan designs. A total of 52 questionnaire copies were distributed. 36 copies of them were collected and the return rate is 77%. Among them, 28 copies were from the engineers and 8 copies were from people in the relevant industries. 22 copies were from males and this accounts for 61%. On the other hand, 14 copies were from females and this accounts for 39%. The results indicated that the weight of efficiency which is the secondary constituent element is the highest. Under the constituent element of efficiency, the weight of fan flow rate is 0.592 which is the highest. The defuzzification of efficiency is 0.744 which is the optimal value among the indices of various factors. The defuzzified value of Design No.4 after defuzzification is 0.682 which is the optimal one among four design candidates. The results of this study demonstrated the feasibility of the proposed design approach. New fan styles can be effectively created by implementing this design approach. This approach allows the entire evaluation process to be more precise. The combination of these approaches is not only practical and objective, but also is capable of assisting a student in making a decision under complicated and uncertain circumstances. This makes a design task definite and better clarified and also enhances a student's learning competitiveness by supplying a good reference during the follow-up stage of product design assessments.

Keywords: fuzzy strategic decision method, fan design, numerical simulation, AHP, fan experiments

INTRODUCTION

Nowadays product requirements by consumers are more and more changeable, and no single product can satisfy the preference of consumers. To cater for consumer demands, the designers must subjectively determine the most relevant conceptual design idea under limited time and resources. However, during the assessment of design concepts, any subjective perception will affect the selection and therefore the designers may fail to make the most objective decision.

A fuzzy optimization model for a fuzzy AHP system has been proposed in this study. To address the inaccuracy of the decision-makers' final decision, a decision model of fuzzy hierarchical analysis has been proposed to be the

Contribution of this paper to the literature

- A new FCE method of product assessment by numerical analysis was proposed for industrial design students.
- An effective approach of evaluating the operation efficiency was proposed.
- Students can now carry out designs effectively and conduct assessments on product design schemes on the basis of competitive selection.

evaluation tool with which the comparison and judgment results by professionals can be transformed into fuzzy numbers. This new approach is different from the conventional method of fuzzy hierarchical analysis and it has been tested and verified by the simulation results conducted. In other words, the problem of fuzzy priorities has been transformed into the testing and verification by simulation models. In addition, to further understand the trend of flow-field distribution of axial fans, performance curves were acquired by wind-tunnel testing according to AMCA 210-85 (Lin, 2004). The results have been compared with numerical ones to check the validity of this approach. The time for trial and error during product design and development is expected to be reduced by this approach and an objective and accurate result is obtained. A ranking of design schemes has been generated based on the design characteristics, and thus the ideal design can be determined.

LITERATURE REVIEW

Hambali (2011) constructed an assessment framework of product designs with an attempt to resolve the problem of vague information during a product design stage. Azadeh (2012) implemented the Fuzzy Synthetic Evaluation (FSE) method to the evaluation of product designs. To reduce the uncertainty and vagueness during the selection of designs (Lin, 2006), the simulation software FLUENT has been used for carrying out the flow-field analysis (Hsiao, 2016; Hsiao, 2017; Hsiao, 2016; Wu, 2016). By means of the fuzzy decision-making method which was combined with hierarchical evaluation targets, Hsiao (1998) has determined the optimal design for fruit juicers from several design schemes. The hierarchical structure was utilized for the quantitative decision on the optimal design scheme. The method can also be used in solving design problems with uncertainties. Hsiao (2006) proposed the principles of grouping and the fuzzy entropy measurements based on a hierarchical AHP, and he applied this approach to the design of homepage formats. The experimental results in his study indicated that the proposed method can be applied to the related design fields such as visual interface designs and graphic designs but not confined to the design assessment of webpage formats. Hsiao (2004) proposed an approach to combine technologies of artificial intelligence including the fuzzy theory, BP neural network (BPN), genetic algorithm (GA), morphological analysis, synthetic evaluation, and the optimization of product designs. Aiming at the inaccuracy of the market information for design schemes, he also utilized the fuzzy theory model to determine product design parameters. In the process of product development in which there is few quantitative information or the information is fuzzy and inaccurate, Huang (2008) utilized the mechanism of fuzzy reasoning and a hybrid learning algorithm for neural networks to establish fuzzy rules and develop a method for determining the membership functions. Korposh and Lee (2011) demonstrated the application of fuzzy AHP from the fuzzy inference to the hierarchical analysis and the ranking of customer demands, and the way to confirm and analyze the priorities and weights of customer demands. Khoo and Chen (2003) proposed a complicated product design scheme which is supported by the fuzzy strategic decision. They also applied the heuristic priority algorithms by the fuzzy analytical hierarchy process to the process of concurrent engineering which is related to all development activities for downstream products. The interaction between such activities increases the complexity, difficulty, and the replicates of product designs, and it can assist in the internal adjustment of design task assignments. With the weights of the fuzzy analytic hierarchy process, Chen (2007) determined the model of allied concurrent engineering (ACE) for enterprises and established the evaluation indices for the hierarchical structures. His approach further incorporated the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and was then applied to the assessment of the adequate enterprises (Lo, 2016; Chang, 2016). This approach can eventually assist in the selection of the optimal enterprise for co-operation and can enhance the effect of synergy for the enterprise alliance. Finally, he introduced examples and conducted real system enforcements to prove the feasibility of the said method.

Analysis by Analytic Hierarchy Process

The analytic hierarchy process was developed by US scholar Thomas L. Saaty in 1971. It is applied on fields with uncertainty and the strategic decision of problems with multiple assessment criteria. Hsiao (2002) used it to conduct the evaluation of design ideas. The hierarchy framework is the major skeleton of the entire system framework, and it has been used to study the interactions of various elements of criteria in the hierarchy and the

influence on the entire system. Furthermore each hierarchy is affected only by another hierarchy (Silvia & Ricardo, 2013; Gorener & Ulucay, 2012; Felice & Petrillo, 2012). A complicated system is simplified as a concise hierarchy system of elements by a nominal scale serving as the pairwise comparison between various hierarchy elements. With the pairwise comparison matrix available, the eigenvectors of the matrix are obtained. They serve as the prioritized vector of said hierarchy and represent the priority of various elements. Eigenvalues can thus be obtained, and they serve as the basis of the degree of consistency of the pairwise comparison matrix. This also serves as the indicator for accepting, rejecting, or re-assessing a strategic decision. The operating procedure consists of six steps which are respectively: (1) analyze the problem and spread assessment indices out; (2) construct the hierarchy framework; (3) establish the dual matrix; (4) seek a solution to eigenvalues and eigenvectors; (5) examine the consistency of the dual matrix; (6) solve for the priority weights of various indices (Subramanian, 2012).

There are numerous parameters affecting the performance of axial fans, therefore a plurality of related indices should be taken into comprehensive consideration to conduct an integral assessment (Chiou, 2009). This approach is the so-called method of FSE. The fuzzy evaluation includes six parts as follows: confirm the affecting factor set, confirm the factor weight set (Khayyam, 2012), confirm the parameter evaluation set, establish factor evaluation matrix, and conduct the fuzzy evaluation along with the processing of evaluation indices (Bellman, 1970; Hsiao, 2004 ; Hsiao, 2006), which are explained respectively as follows (Hu, 2011; Asadzadeh,2011):

Fuzzy Synthetic Evaluation

There are numerous parameters affecting the performance of axial fans, therefore a plurality of related indices should be taken into comprehensive consideration to conduct an integral assessment (Chiou, 2009). Related indices should be taken into comprehensive consideration to conduct an integral assessment (Chiou, 2009). Nepal (2010) proposed a method of fuzzy-AHP based on the fuzzy set theory for the determination of design planning and the ranking of customer satisfaction. Customer demands can be determined by the presentation of a case study in the automotive industry, and this approach can be incorporated into the design and development processes of concept cars. However, this approach lacks quantitative data and the relationship between various attributes is not defined. This drawback results in the difficulty in developing a quantitative model for the analysis and determination of satisfactory attributes for customers. As a result, it is very important to determine the decision factors for a car deal and the car industry can use these factors to leverage car characteristics. The priority of these factors can help determine the critical portions for improvement which can also be the design targets for the next generation. Customer satisfaction is generally the top consideration for the development of vehicle attributes with the ultimate goal of increasing the market share. This approach is the so-called method of FSE. The fuzzy evaluation includes six parts as follows: confirm the affecting factor set, confirm the factor weight set (Khayyam, 2012), confirm the parameter evaluation set, establish factor evaluation matrix, and conduct the fuzzy evaluation along with the processing of evaluation indices (Bellman, 1970; Hsiao, 2004 ; Hsiao, 2006), which are explained respectively as follows (Hu, 2011; Asadzadeh,2011).

RESEARCH METHODS

The evaluation approach proposed in this study not only conducts the flow-field analysis of fans, but also conducts the research method for the selection of axial fans by integrating the synthetic evaluation method and AHP (Liu et al, 2012; Peng, 2012).The theoretical foundations of each methodology are briefly explained as follows:

Analysis by Analytic Hierarchy Process

Establishing affecting factor set. When conducting the fuzzy evaluation, the first step is to confirm the factors affecting the values of evaluation parameters. If it is known that the affecting factors are $u_1, u_2, …, u_m$, then the factor set composed of these parameters is $U=\{u_1, u_2, …, u_m\}$, and this factor set is a common set (Lata, 2012).

Determining factor weight set. To reflect the degree of importance of each factor, each factor u_i should be assigned a corresponding weight w_i. Since the degree of importance of each factor may possibly be different, a weight can be assigned to each factor. The aggregation composed of the weights thus becomes the factor weight set, which is represented as $W=\{w_1, w_2, …, w_m\}$. If w_i indicates the weight of the ith factor, then the weight of each factor should satisfy Eq. (1). It can be represented as a fuzzy subset of the factor set, and the weight set is represented by Eq. (2).

$$\sum_{i=1}^{m} w_i = 1 \quad , \quad w_i \geq 0 \quad (i = 1, \quad 2, \quad 3,…,m) \tag{1}$$

$$\widetilde{W} = \frac{w_1}{u_1} + \frac{w_2}{u_2} + \frac{w_3}{u_3} + \cdots + \frac{w_m}{u_m} = (w_1, w_2, w_3, \cdots, w_m) \tag{2}$$

where the weight of each factor could be determined by means of weighted coefficient method, the analysis by AHP (Cheng et al.,2012), and paired comparison method or confirmed subjectively based on those required by the real problem. The weights are obtained by the analysis of analytic hierarchy process which was developed by (Hsiao, 2006), and examined against the consistency to enhance the reliability (Tummala, 1998).

Fuzzy Synthetic Evaluation

Determining parameter evaluation set. An evaluation set is the aggregation composed of various kinds of assessment results on the targets of evaluation by the assessor. It is represented by V , which is $V=\{v_1, v_2, …, v_n\}$, and v_i (i =1,2,3,…,n) represents various kinds of possible results of the overall assessment. The purpose of fuzzy evaluation is to obtain the best assessment result from the evaluation set on the basis of considering all affecting factors comprehensively. The relationship between v_i and V is also a relationship in the form of common set. Therefore an evaluation set is also a common set and the evaluation set is V= {completely agree, agree, neither agree nor disagree, disagree, completely disagree}.

Establishing factor evaluation matrix. The single factor fuzzy evaluation is to judge one factor separately (Jiao, 1998), and to confirm the degree of membership (DOM) for the target of evaluation toward evaluation-set elements. If the target of evaluation in the factor set is the ith factor U_i , the membership grade of the j th element V_i in the evaluation set is r_{ij} , then according to the results of assessments on the ith factor U_i , it can be represented by the fuzzy set as follows:

$$\tilde{R}_i = \frac{r_{i1}}{v_1} + \frac{r_{i2}}{v_2} + \cdots + \frac{r_{in}}{v_n} = (r_{i1}, r_{i2}, …, r_{in}) \tag{3}$$

where $\tilde{R}_i$ is called the single-factor evaluation set, it is a fuzzy subset of the evaluation set, which can be represented as $\tilde{R}_i=(r_{i1}, r_{i2},…,r_{in})$. The single-factor evaluation set corresponding to each factor is similarly available as follows:

$$\tilde{R}_1 = (r_{11}, r_{12}, …, r_{1n})$$
$$\tilde{R}_2 = (r_{21}, r_{22}, …, r_{2n})$$
$$\vdots$$
$$\tilde{R}_m = (r_{m1}, r_{m2}, …, r_{mn}) \tag{4}$$

The fuzzy matrix composed of the membership grade of each single-factor evaluation set is

$$\tilde{R} = (r_{ij})_{m \times n} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{5}$$

Eq. (5) shown above is called the single-factor assessment matrix (Kuo, 2006). $\tilde{R}$ is a fuzzy matrix, which can be viewed as the fuzzy relational matrix from U to V (i.e., fuzzy mapping). However in this study, due to numerous factors to be considered, it is difficult to obtain a reasonable evaluation result by a single-factor fuzzy evaluation since each factor usually possesses a differing hierarchy. Therefore, the multi-level Fuzzy Comprehensive Evaluation (FCE) was implemented in this study. Basaran (2012) proposed an approach of conducting a FCE on the basis of another FCE and his approach can be carried out iteratively based on demands. Since there are numerous factors to be considered in complicated selection and factors are further divided into levels, the multi-factor assessment matrix should be used for resolving the problem. The factor set should then be divided into several levels according to its characteristics (Calvino, 2010). Firstly the combined evaluation is conducted on each level, and then in-depth combined evaluations on the evaluation results are conducted (Moon and Jung, 2011).

Conducting fuzzy composite operations. If the fuzzy evaluation matrix of a certain scheme onto the evaluation target is as Eq. (5), considering the weighted comprehensive fuzzy evaluation, the product of fuzzy matrices is then

$$\tilde{B} = \tilde{W} \bullet \tilde{R} = (b_1, b_2, … b_j, … b_n) \tag{6}$$

where symbol "$\bullet$ "represents fuzzy composite operations. By means of the weight fuzzy matrix $\tilde{W}$, and factor judgment matrix $\tilde{R}$; there are many kinds of composition methods shown as follows (Hsiao, 1998).

Model 1   When applying the composition by algorithm M($\wedge$, $\vee$), the result is

$$b_j = \bigvee_{i=1}^{m} (w_i \wedge r_{ij}) \qquad ; \qquad j = 1, 2, …, n \tag{7}$$

Model 2   When applying the composition by algorithm M($\bullet$, $\vee$), the result is

$$b_j = \bigvee_{i=1}^{m} (w_i r_{ij}) \qquad ; \qquad j = 1, 2, …, n \tag{8}$$

Model 3   When applying the composition by algorithm M($\wedge$, +°), the result is

$$b_j = min\{ \ 1, \ \sum_{i=1}^{m}(w_i \wedge r_{ij})\} \qquad ; \qquad j = 1, \ 2, \ \dots, \ n \tag{9}$$

Model 4   When applying the composition by algorithm M(• , +°), the result is

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

This model is also called weighted-average (WA) type, and its characteristic is that when w_i is provided with normalization, i.e., $\sum\limits_{i=1}^{m} w_i = 1$, $\sum\limits_{i=1}^{m} w_i r_{ij} << 1$, then said model will be adapted as M(• , +), and then

$$b_j = \sum_{i=1}^{m}w_i r_{ij} \qquad ; \qquad j = 1, \ 2, \ \dots, \ n \qquad ; \qquad \sum_{i=1}^{m}w_i = 1 \tag{11}$$

This model not only considers the influence of all factors, but also keeps the entire message of the single-factor evaluation. When in operation there is no confinement for w_i and r_{ij} on the upper limit, and it is only required to perform normalization on w_i. This is the prominent characteristic and merit of this model (Choi, 2011).

The principles of Model 1 to 3 are all in search of individual evaluation result under a condition of taking limit values with a certain kind of limitation. Therefore, to varying degrees it will lose a lot of useful information during the evaluation process. This can be used in occasions only concerned with the limit values of things and with an intention to make a certain primary factor stand out. Based on this, Model 4 is adopted as the operational method for composition in this study (Tsaur, 2002).

Processing of evaluation indices. After obtaining evaluation indices b_j (j =1,2,…,n) , the concrete results of the target of evaluation can thus be confirmed based on the method of maximum DOM and WA method, and they are explained as follows (Wang, 1995; Tsai, 2004; Farzaneh, 2008).

1) Maximum DOM

In light of the principle of maximum membership, the corresponding evaluation element v_i to the largest evaluation index b_j is selected as the evaluation result. This method considers only the contribution of the maximum evaluation index, and discards the information provided by other indices. Besides, when the number of the largest evaluation indices is more than one, it is hard to determine any concrete evaluation result by the method of maximum DOM. Therefore the WA method will usually be adopted.

2) WA method

b_j is taken as the weighting factor, and each evaluation element v_j taken as the result of evaluation by carrying out the weighted average (Caputo, 2000), i.e.,

$$D = \frac{\sum_{j=1}^{n} b_j v_j}{\sum_{j=1}^{n} b_j} \tag{12}$$

When the evaluation index bj is normalized, then

$$D = \sum_{j=1}^{n} b_j v_j \tag{13}$$

If the targets of evaluation are quantitative numbers, the value of D is calculated by Eq. (13). This value is thus the result of conducting FCE on the said quantity. If the targets of evaluation are non-quantitative numbers, for example if the evaluation set is {Excellent, Good, Fair, Bad}, then for the time being it is required to apply quantification on non-quantitative numbers of Excellent, Good, Fair, Bad. Or otherwise the method of maximum DOM must be adopted. Through various evaluation standards mentioned above, the distribution status of the target of evaluation in the characteristic aspect being evaluated can be concretely reflected. The referee can then have an even thorough understanding of the target of evaluation, and can handle this with good flexibility.

Numerical Analysis

In three-dimensional Cartesian coordinates, the flow field can be solved by governing equations of continuity, momentum, and energy. Based on fundamentals of the finite-volume method, the computational domain must be partitioned into many small control volumes. After a volume integral, the equations of mass, energy, and momentum of fluids can then be transformed into algebraic equations for numerical calculations.

Theory of Turbulence Model

Since turbulence causes the exchange of momentum, energy, and concentration between fluids, it causes fluctuations. Such fluctuations are of small scale and with a high frequency. Therefore, when simulating turbulent flows, manipulations on the control equations are required for filtering out turbulence components which are at extremely high frequency or of extremely small scale (Liu, 2013). However the modified equations may comprise variables which are unknown to us, while the turbulence model requires known variables to confirm these variables. The standard $k - \varepsilon$ turbulence model is selected for the calculation of flow fields in this study (Chang, 2010).

Performance Testing Equipment for Wind Turbines

The main device of the performance testing equipment for fans is an outlet-chamber wind tunnel which conforms to AMCA 210-99. The principal parts include flow setting means, multiple nuzzles, flow-rate regulating devices, etc. The major function is to supply a good and stable flow field for measurement, and to acquire the complete performance curves (Carolus, 2007).

CASE VERIFICATION AND ANALYSIS

Classification of Factors

Firstly evaluation indices for axial fans are determined by classifying factors. To identify the relevance of evaluation indices, semi-structural interviews have been adopted to survey the opinions of professionals in related fields. They made professional judgments of their own and conducted an assessment on the importance of each factor. Evaluation indices are thus established and further grouped into three levels. The first level is the goal level, which is the eventual goal of the evaluation on axial fans. The second level is the objective level, which includes functionality, efficiency, aesthetics, creativeness, and economy. The third level covers nineteen items of assessment criteria. It is already known that there are numerous factors affecting fan evaluations, and therefore it is required to apply quantization on the degree of influence of various factors. The degrees of influence of various factors are calculated by systematic approaches, and quantization results can thus be obtained.

Sampling Technique

Based the general principles of the judgment time, cost, and objective for the experts, the purposive sampling technique was implemented in this study. The most typical representing samples were selected by human will from the population as the investigation targets. The main effect of AHP is on its nominal scale, which is used for the pairwise comparison of the elements between the hierarchies. A 9-point scale is formed by adding four points into the intervals of a 5-point scale. Since the questionnaire that is used during the AHP analysis is realized by a survey conducted on experts, the respondents were limited to experts that were able to answer to the questions. Moreover, a structured questionnaire survey is carried out in a quantitative way. Therefore, a total of 52 questionnaire copies were distributed to experts that are related to industrial design and fan design jobs. These respondents include 34 design-related and industrial design-related engineers and 18 design managers and salespeople in the related industries. A total of 36 questionnaire copies were returned and the rate of response is 77%. These included 28 copies from the engineers and 8 copies from those in the related industries. The respondents who returned the questionnaire copies include 22 males and 14 females and the percentages by gender are 61% versus 39%.

Instruments

A 5-point scale was used in the questionnaire for the assessments in this study. The scale indicates a respondent's level of agreement or disagreement on the importance of an item in the range of 5~1, which stand for completely agree, agree, neither agree nor disagree, disagree, completely disagree respectively. Any item that scores 20 points or more is viewed as an important assessment item and is included into the hierarchical framework. An item is viewed as not important if it scores less than 20 points and is excluded from the hierarchical framework. The results of the questionnaire survey on 6 professionals indicated that two evaluation attributes among the constituent elements of functionality scored more than 20 points. These two attributes included "convenience" and "unified pattern and function". The attribute that scored the highest at 28 points was the "market scale". Four evaluation attributes among the constituent elements of performance scored more than 20 points and they are respectively "power-saving", "noise level", "air flow rate of a fan", and "variation in LED characters". The attribute that scored the highest at 29 points was the "air flow rate of a fan". Four evaluation attributes among the constituent elements of aesthetics scored more than 20 points and they are respectively "product texture", "appearance and
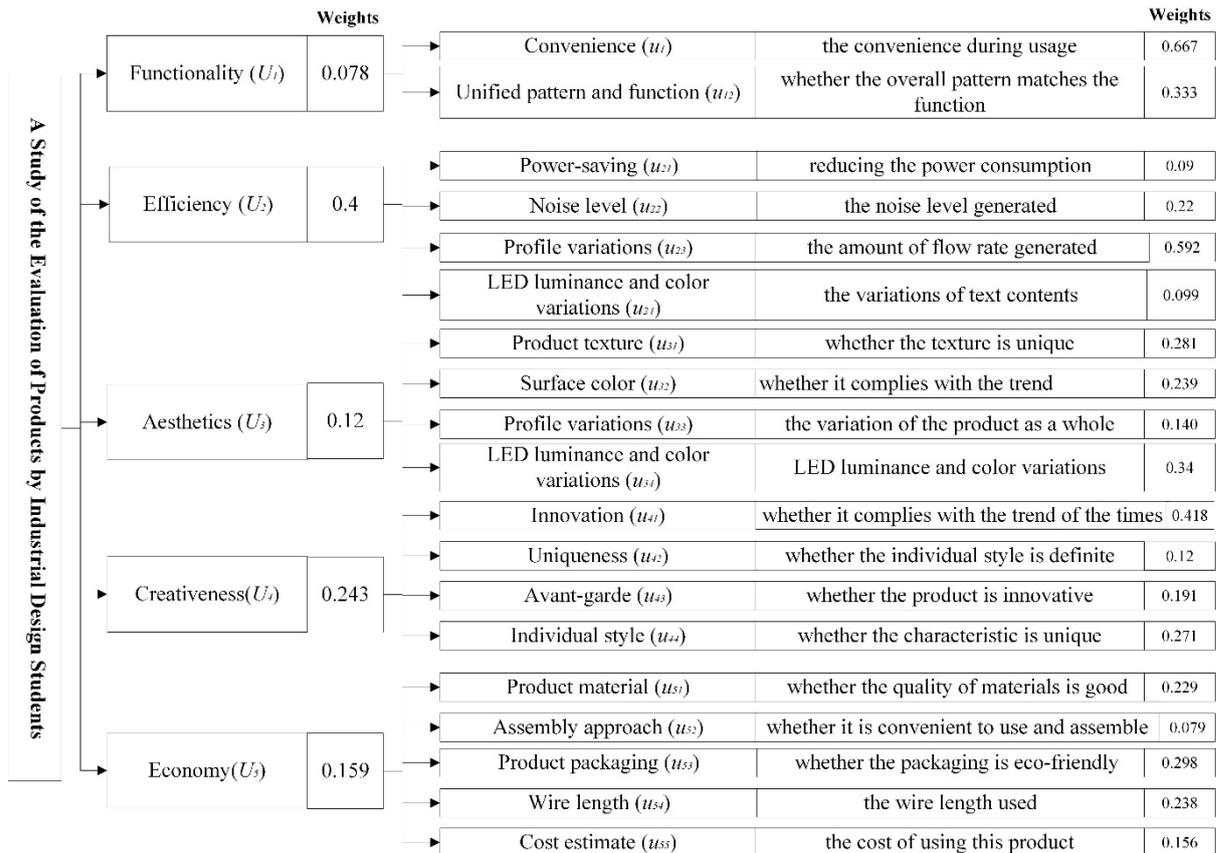
Figure 1. Evaluation indices for axial fans for personal computers

color", "variations in profile", and "variations in LED brightness and colors". The attribute that scored the highest at 29 points was the "product texture". Four evaluation attributes among the constituent elements of creativeness scored more than 20 points. Two attributes which include the "uniqueness of innovation elements" and "individual style in parallel" scored the highest at 26 points. Five evaluation attributes among the constituent elements of economy scored more than 20 points and they are respectively "product materials and assembly approach", "product packing", "wire length", and "cost estimation". The results obtained from the questionnaire survey on the experts indicated that, a complete hierarchical framework can be constructed by "functionality", "performance", "aesthetics", "creativeness", and "economy". The questionnaire is based on the AHP and it consists of seven portions including research's letter of instruction, instructions for filling the questionnaire and examples, the criteria of the intensity of importance, hierarchical framework of indices, expatiation, and questions. Pairwise comparisons of the importance between two elements were carried out within each sub-system.

Sample Size

The results by questionnaire have been processed by quantization. 36 professionals were interviewed, and they comprise 28 proprietors in fan-related industries and 8 employees related to fan industries. Factors of evaluation indices for axial fans have been evaluated (as shown in **Figure 1**), and AHP and FCE have been conducted. The calculation of evaluation indices was conducted by means of Model 8 of fuzzy composition method to obtain the final evaluation results.

RESEARCH DESIGN

It is known from AHP that when $C.R. \leq 0.1$, this indicates that the evaluation matrix possesses the satisfying consistency and the weight distribution is reasonable. The C. R. values of upper-level indices of the evaluation indices of fans are all 0.04. Among lower-level indices, the C. R. value of "function" is 0.01; that of "efficiency" is 0.01; that of "aesthetics" is 0.03; that of "creativity" is 0.02; that of "economy" is 0.02. Since they are all smaller than 0.01, it can be determined that the evaluation matrix possesses satisfying consistency, which indicates that the weight distribution is reasonable. The examination of consistency of the overall hierarchy of questionnaire is then

determined by the ratio of overall consistency, which is 0.02. Since it is smaller than 0.1, this indicates the assessment of the entire hierarchical framework is acceptable.

The weight sets of various indices can be obtained through above-mentioned research results and Eq. (2):

$\widetilde{W}_1 = [0.75,$		$0.25]$		$\widetilde{W}_2 = [0.079,$	$0.284,$	$0.549,$	$0.088]$
$\widetilde{W}_3 = [0.365,$	$0.235,$	$0.120,$	$0.281]$	$\widetilde{W}_4 = [0.477,$	$0.119,$	$0.221,$	$0.183]$
$\widetilde{W}_5 = [0.179,$ $0.093,$ $0.313,$ $0.240, 0.174]$				$\widetilde{W} = [0.103,$ $0.442,$	$0.125,$	$0.134,$	$0.132]$

Fuzzy Comprehensive Evaluation

The evaluation set is defined as V={completely agree, agree, neither agree nor disagree, disagree, completely disagree}. According to all the data collected, the fuzzy evaluation matrix of each factor can be built and the fuzzy set is shown as follows:

$$\tilde{R}_1 = \begin{bmatrix} 0.291 & 0.436 & 0.227 & 0.045 & 0.00 \\ 0.369 & 0.246 & 0.249 & 0.135 & 0.00 \end{bmatrix}$$

$$\tilde{R}_2 = \begin{bmatrix} 0.264 & 0.281 & 0.342 & 0.113 & 0.00 \\ 0.188 & 0.349 & 0.307 & 0.156 & 0.00 \\ 0.426 & 0.213 & 0.287 & 0.075 & 0.00 \\ 0.302 & 0.302 & 0.241 & 0.154 & 0.00 \end{bmatrix}$$

$$\tilde{R}_3 = \begin{bmatrix} 0.272 & 0.289 & 0.298 & 0.141 & 0.00 \\ 0.291 & 0.436 & 0.227 & 0.045 & 0.00 \\ 0.175 & 0.398 & 0.349 & 0.078 & 0.00 \\ 0.231 & 0.351 & 0.305 & 0.113 & 0.00 \end{bmatrix}$$

$$\tilde{R}_4 = \begin{bmatrix} 0.296 & 0.374 & 0.236 & 0.094 & 0.00 \\ 0.279 & 0.205 & 0.402 & 0.115 & 0.00 \\ 0.274 & 0.354 & 0.269 & 0.103 & 0.00 \\ 0.274 & 0.353 & 0.306 & 0.067 & 0.00 \end{bmatrix}$$

$$\tilde{R}_5 = \begin{bmatrix} 0.285 & 0.270 & 0.272 & 0.173 & 0.00 \\ 0.296 & 0.374 & 0.236 & 0.094 & 0.00 \\ 0.276 & 0.285 & 0.267 & 0.173 & 0.00 \\ 0.273 & 0.410 & 0.235 & 0.081 & 0.00 \\ 0.276 & 0.285 & 0.267 & 0.173 & 0.00 \end{bmatrix}$$

With the fuzzy evaluation matrix of each factor being established, Model 4 of fuzzy composition method was adopted and the results of the comprehensive evaluation being conducted are as follows. For the assessment of lower hierarchies:

Functionality: $\tilde{B}_1 = \widetilde{W}_1 \bullet \tilde{R}_1 = [0.296 \quad 0.374 \quad 0.236 \quad 0.094 \quad 0.00]$

Efficiency: $\tilde{B}_2 = \widetilde{W}_2 \bullet \tilde{R}_2 = [0.423 \quad 0.212 \quad 0.285 \quad 0.080 \quad 0.00]$

Aesthetics: $\tilde{B}_3 = \widetilde{W}_3 \bullet \tilde{R}_3 = [0.272 \quad 0.289 \quad 0.298 \quad 0.141 \quad 0.00]$

Creativeness: $\tilde{B}_4 = \widetilde{W}_4 \bullet \tilde{R}_4 = [0.291 \quad 0.436 \quad 0.227 \quad 0.045 \quad 0.00]$

Economy: $\tilde{B}_5 = \widetilde{W}_5 \bullet \tilde{R}_5 = [0.268 \quad 0.305 \quad 0.259 \quad 0.168 \quad 0.00]$

As for the assessment of higher hierarchies, the weights of indices of higher hierarchies are known in **Figure 2(a)** and the evaluation matrix of indices of higher hierarchies is

$$\tilde{R}^* = \begin{bmatrix} \tilde{B}_1 \\ \tilde{B}_2 \\ \tilde{B}_3 \\ \tilde{B}_4 \\ \tilde{B}_5 \end{bmatrix} = \begin{bmatrix} 0.296 & 0.374 & 0.236 & 0.094 & 0.00 \\ 0.423 & 0.212 & 0.285 & 0.080 & 0.00 \\ 0.272 & 0.289 & 0.298 & 0.141 & 0.00 \\ 0.291 & 0.436 & 0.227 & 0.045 & 0.00 \\ 0.268 & 0.305 & 0.259 & 0.168 & 0.00 \end{bmatrix}$$

Therefore, the results of FCE of higher hierarchies are

$$\tilde{C} = \widetilde{W} \bullet \tilde{R}^* = [0.423 \quad 0.212 \quad 0.285 \quad 0.080 \quad 0.00]$$

As for the processing of evaluation indices, typical methods in common use are the method of maximum DOM and the WA method. Among them, the WA method is one of the methods that can transform fuzzy values into definite values in the same way as defuzzification. The purpose of defuzzification is exactly to transform the final data and results of fuzzy properties into definite numerical data. By applying defuzzification on these fuzzy values, they turn into definite values with representativeness. Thus the evaluation set V can be assigned as V={1, 0.75, 0.50, 0.25, 0}. The defuzzified values D of evaluation results are obtained by calculations and the results are shown in **Figure 2 (a)** and **Figure 2(b)**.
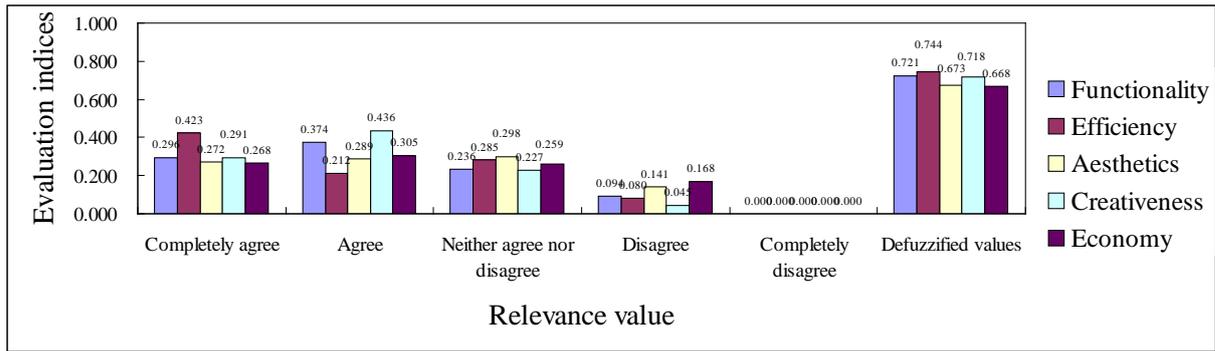
(a)
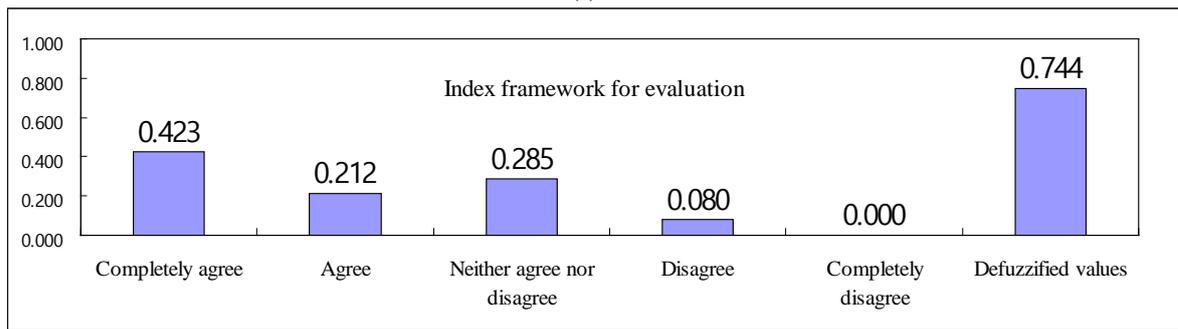
(b)

Figure 2. (a) Degrees of conformity of various indices. (b) Degrees of conformity of the index framework for evaluation

Table 1. Comparison between results by numerical simulation and experiment testing

	Numerical simulation	Experiment testing	Tolerance
Flow rate	16.8CFM	16.3CFM	3%
Static pressure	1.75mm-H2O	1.71mm-H2O	2%

The evaluation of axial fans has been conducted through the fuzzy theory, and the research results are shown in **Figure 2(a)** and **Figure 2(b)**. In the research process it was discovered that, the factor weights are 0.423 for "efficiency" and 0.296 for "functionality" respectively. This agrees with the resulting ranking obtained by the FSE. However, values of the pairwise comparison matrix in AHP are provided with concerns of subjectivity, inaccuracy, vagueness, etc. To resolve these concerns, AHP has been therefore extended to a fuzzy environment, which can make up for the deficiency of AHP failing to solve the problem of fuzziness. Subsequently, items for assessment are then selected via FSE, and the fuzzy scores of various assessment indices are obtained and they serve as the selection standard. It also reveals from the results of **Figure 2(b)** that, the overall index of the assessment on axial fans is 0.744 and it is between levels of "completely agree" and "agree". This indicates that the framework of evaluation indices for the design optimization of axial-flow fans is acceptable.

Verification between Numerical Simulation and Experiment Testing

Mock-up samples were built for wind-tunnel testing and the results have been compared with those by simulation. The geometric parameters of the final design are shown in Appendix1.

It is known from **Table 1** that the simulation results obtained are about 3% lower than the counterparts by experiment testing. After further investigation, it was found that this mostly comes from the difference between the real-test environment and the simulation configuration (as shown in **Figure 3**). Since the resistance of a fan varies at different points of operation and the average rotation speed during the entire testing process is 3% larger than design rotation speed, it is recommended increasing the rotation speed 2~4% and this can compensate for the tolerance.

0.0   1.2   2.4   3.6   4.8   6.0   7.2   8.4   9.6   10.8   12.0

Contours of Velocity Magnitude (m/s)

Aug 31, 2013
FLUENT 6.3 (3d, pbns, rke)

(a) Flow field distribution

Convergence history of Mass Flow Rate on pressure_outlet.2

Aug 31, 2013
FLUENT 6.3 (3d, pbns, rke)

(b) Number of iterations

Scaled Residuals

Aug 31, 2013
FLUENT 6.3 (3d, pbns, rke)
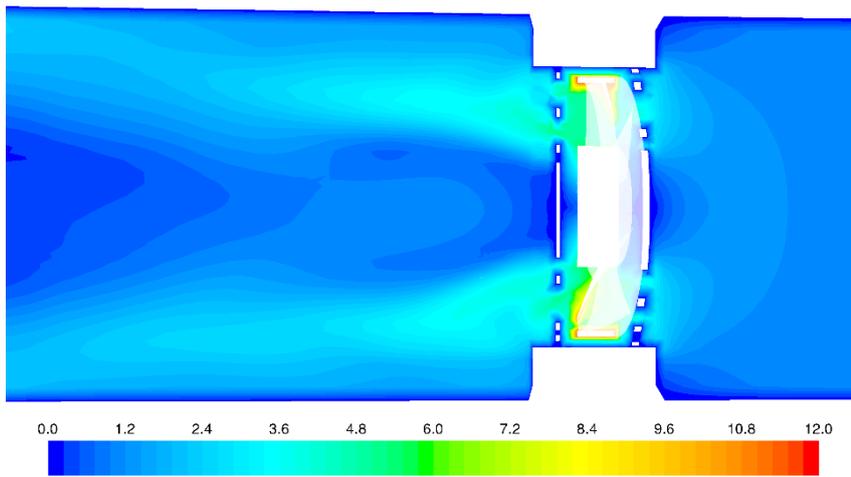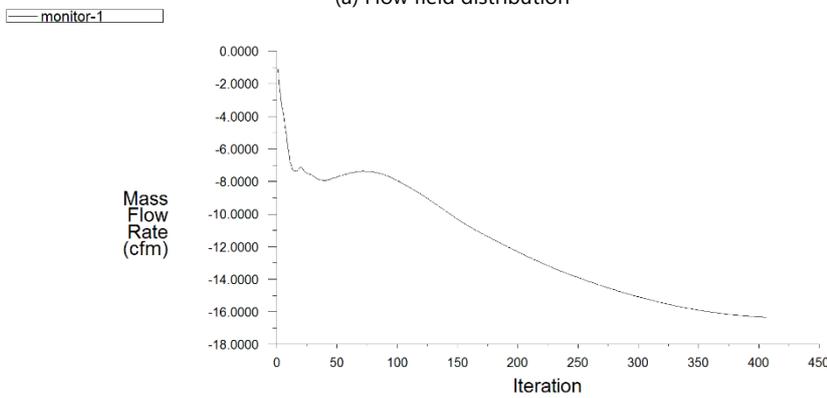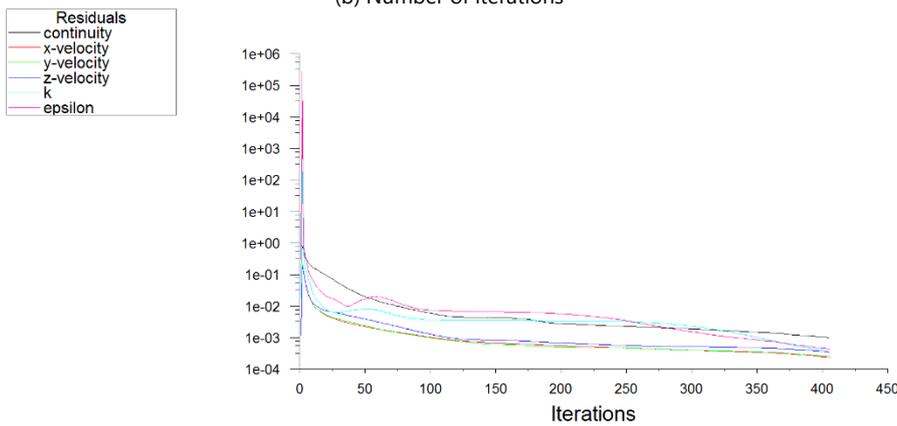
(c) Convergence plot

Figure 3. Results of numerical simulation

No.	Design proposals	Design name	Content descriptions of design proposals	Simulation results
Idea-1		Eastern style	The presentation of styles of simplicity, calmness, and inward-looking, and it also possesses a special flavor of primitive and simplicity of the eastern world.	
Idea-2		A flower with four petals	It resembles a cross corolla formed by four petals, and the structure in the grille divides the inside into four groups of vents. The structure resembles the principal part of petals.	
Idea-3		Bubble holes	Bubble holes are employed and they serve as the major design idea, while small openings are added into the design as well.	
Idea-4		Honeycomb	With a meshed structure composed of honeycombs, this should a better design with enhanced structural strength and reduced flow impedance.	
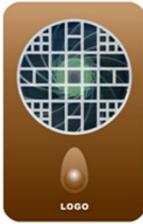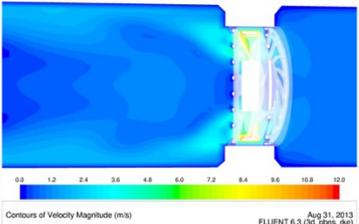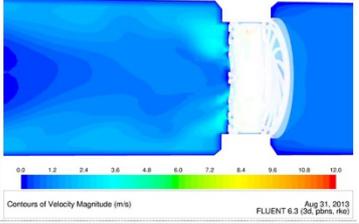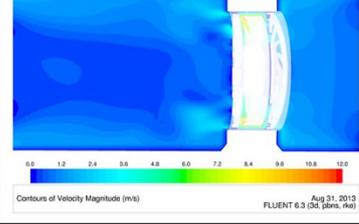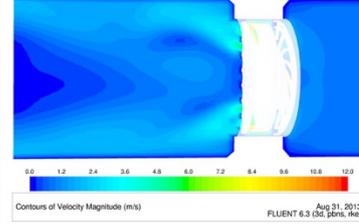
Figure 4. Design cases and content descriptions

DESIGN CASES AND COMPARISON BETWEEN SIMULATION RESULTS

Four kinds of different patterns of axial fans have been finally designed and the external forms are shown in **Figure 4**. Upon the completion of these four kinds of different designs, further assessments by simulation were conducted on them for analysis and comparison. To make the simulation more meaningful, identical simulation conditions are applied on all four cases.

The observation from a plane above the impeller intake indicates that the stream line distribution of No.3 at the inlet is greatly affected by the turbulent flow. On the contrary, No.4 is hardly affected and the air flows through the honeycomb structure and finally into the atmosphere. The flow field variations around the impellers of No.1 and No.2 are both very large. And recirculation occurs at the downstream for No.1 and No.3. This obviously impacts on the performance and results in lower flow rates **Figure 4**.

It can also be discovered at the downstream prior to the outlet that, flows collide with each other behind the impeller region in No.1 and No.3 and this greatly affects the flow smoothness at the outlet. For No.1, No.2, and No.3, the adverse influence of the external forms may contribute to the reduction of outlet flow rate. More than that, the vortices that occurred in No.1, No.2, and No.3 disturbed the smoothness of flow fields, and then affected the flow conditions downstream the impeller. The maximum flow velocity of No.4 is higher than those of No.1, No.2, and No.3. This also indicates that the flow field of No. 4 is smoother and the flow rate obtained is also the highest. After the fluid flows through the blades, it may subject to the influence of the outlet profiles. The geometry of No.4 creates less resistance and facilitates the airflow all the way to the outlet. A higher flow rate is the evidence of the smoothness of the airflow.

(a)

(b)
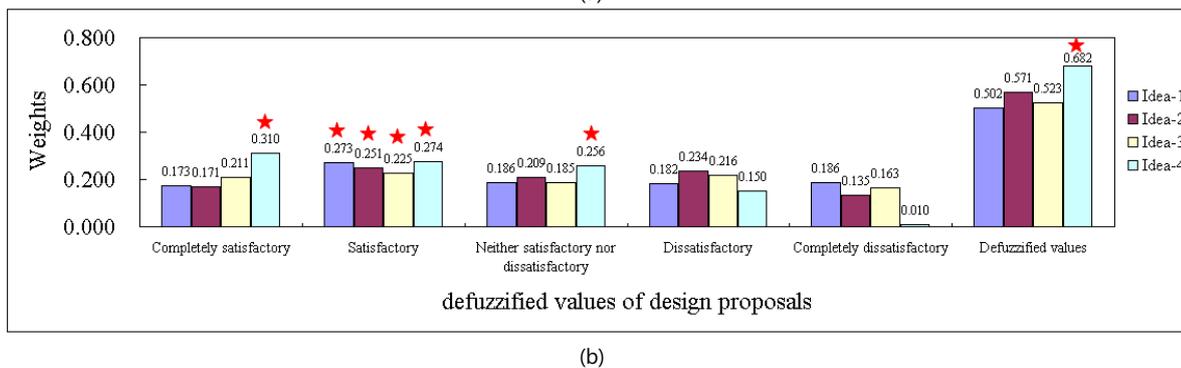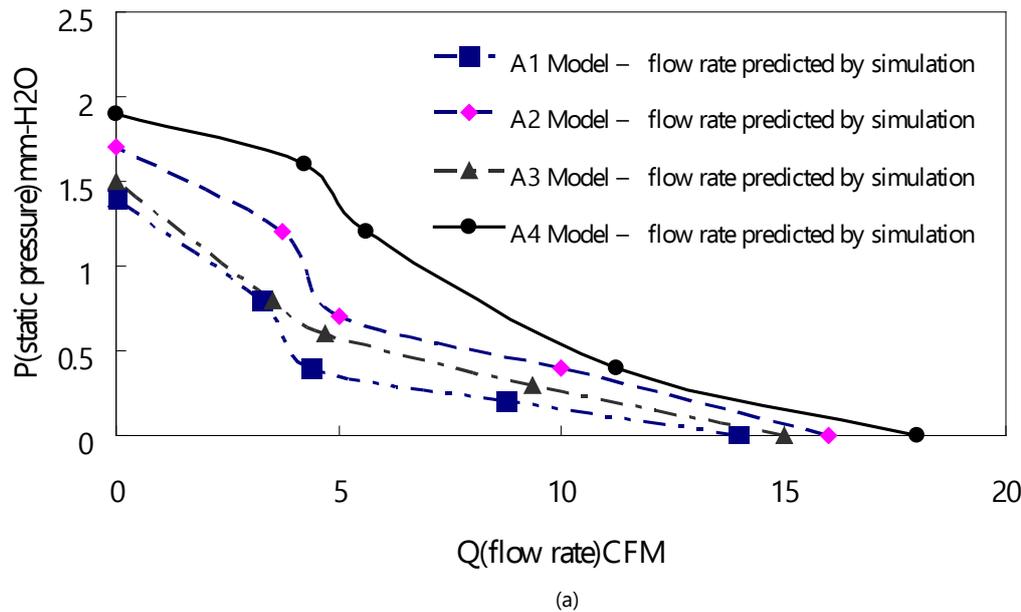
Figure 5. (a) Performance curves of four models based on values by numerical simulation and (b) Degrees of satisfaction and defuzzified values of design proposals
Note: Values marked with '*' have the highest degree of satisfaction

The simulated flow rates in **Figure 5(a)** indicate that for No.4 with a rotation speed of 2000 rpm, the flow rate calculated is 18 CFM. On the other hand, the flow rate of No.2 is 16 CFM, which is 2 CFM smaller than that of No.4. The maximum static pressure of No.4 is 1.87 mm-H2O, and this is the highest among all four models. For comparison, the maximum static pressure of No.2 is only 1.74 mm-H2O. Therefore, No.4 is the best design among all four models since it has both the highest maximum flow rate and highest maximum static pressure.

Figure 5(b) indicated that blade profile design is also an important part of the study on the aesthetic perception of styling. The defuzzified value of No.4 after defuzzification is 0.682, which indicates the design is satisfying. Secondly, the defuzzified value of No.1 is 0.502, which indicates neither satisfactory nor dissatisfactory. Therefore the results of the overall evaluation indicated that No. 4 is the most popular design for the subjects. This design proposal not only integrates functionality and aesthetics, it even takes economy into consideration. Performance-wise, it is the best among all four design proposals. It is thus concluded that No. 4 is the optimal design proposal from the aspect of overall design.

The evaluation of fans was carried out in this study by the fuzzy theory. The resulting ranking is the same as the one that was obtained by the FSE approach. However, the pairwise comparison matrix obtained by the AHP has problems with its subjectivity, inaccuracy, and vagueness. Therefore, we extended the AHP into the fuzzy environment in order to resolve these problems. This approach can make up for the AHP's deficiency of not being able to resolve the problem of vagueness. After that, the FSE can be used for selecting the items for assessment in order to obtain the fuzzy scores of each evaluation indices as the selection criteria. The results obtained by this study can be viewed as a dual verification, which indicated that both approaches have results in common to a certain degree and therefore the accuracy of this research can be further enhanced.

Results Obtained by the FSE Design Approach

When there is a plurality of design proposals, index weights can be firstly confirmed by means of the evaluation system proposed to determine the degree of influence of each index on the overall performance. This results in a further optimization of the design process. However when the performance indices cannot be made quantitative, the assessment values of various elements with qualitative indices can be configured by the method of FSE. The evaluation matrices are thus created and FSE can be conducted to find most adequate design scheme. This evaluation method is beneficial to the quantification of qualitative indices, and it helps reduce the subjectivity, which also facilitates the design process. By integrating styling aesthetics when investigating fan characteristics, the aesthetics of fan products can be enhanced. Previously, designers considered only the subjective consciousness of their own. By integrating the fuzzy theory, the importance of each factor can be effectively highlighted.

CONCLUSIONS

Within existing literature, the evaluation approaches used by many decision-makers usually take single index which could be either the minimum cost or the maximum benefit as the evaluation criteria. However, a decision-maker is facing more complex problems in the diversified and complicated social environment. It is also required to leverage between various conflicting goals. Therefore, using a single criterion for selecting or assessing design schemes is not well thought-out and neither does it meet the requirements of practical problems. Due to the fact that the typical AHP approach doesn't satisfy industrial design students' requirement of determining the critical factors of product assessment, a new evaluation approach that integrates AHP, fuzzy theory, and numerical analysis was proposed in this study. Firstly, AHP was implemented during the calculation of weights that affect the importance of performance parameters. After that, the FCE approach was implemented on the degrees of satisfaction of various parameters. Numerical analyses were carried out in order to obtain the performance curves of design models and the results were further compared with the measurements by real testing. Model No.4 was verified to be the optimal design among all of the design proposals since it presented the largest weight. The result that was obtained by implementing the defuzzified values to obtain the fuzzy weights also agreed with the results obtained by numerical analyses. The engineering evaluation required to be carried out on the overall design of any fan products can be achieved by the fuzzy decision-making method. The emphasis of this approach is on a new assessment method for the overall profile and performance of design proposals. The procedure and framework proposed in this study for evaluating product design schemes are verified to be practical and objective so that the quality of a decision on product designs can be greatly enhanced.

RECOMMENDATIONS

Although the new evaluation approach that was proposed in this study has been verified to be effective in determining the critical factors of product assessments, the evaluation indices are limited to fan profile and performance. For follow-up studies, a more comprehensive investigation is recommended to include other critical indices including manufacturing cost, noise level, electromagnetic characteristics, etc. The indices that were investigated in this study are relatively simpler since they do not interact with each other. However, in real industrial designs with complicated design considerations, each of the indices might interact with the others. In this case, the defuzzified values that are used for obtaining the fuzzy weights might not be independent. The evaluation approach of this study should be further improved by taking this dependency into consideration.

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APPENDIX

Appendix 1. Blade Parameters

Airfoil profile	NACA 65-Series
Airfoil name	NACA 65-Parabolic arc
Blade count	7
Hub radius	8
Blade-tip radius	36
Outside radius of housing	40
Blade tip clearance	0.75
Incidence angle of the blade at the hub	50
Incidence angle of the blade at the tip	35
Blade width at the hub	11
Hub thickness	23.5
Number of sections	31

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