A Design for Supply Chain Model by Integrated Evaluation of Design Value and Supply Chain Cost

Yuan-Jye Tseng, Jia-Shu Li

Abstract**—**To design a product with the given product requirement and design objective, there can be alternative ways to propose the detailed design specifications of the product. In the design modeling stage, alternative design cases with detailed specifications can be modeled to fulfill the product requirement and design objective. Therefore, in the design evaluation stage, it is required to perform an evaluation of the alternative design cases for deciding the final design. The purpose of this research is to develop a product evaluation model for evaluating the alternative design cases by integrated evaluating the criteria of functional design, Kansei design, and design for supply chain. The criteria in the functional design group include primary function, expansion function, improved function, and new function. The criteria in the Kansei group include geometric shape, dimension, surface finish, and layout. The criteria in the design for supply chain group include material, manufacturing process, assembly, and supply chain operation. From the point of view of value and cost, the criteria in the functional design group and Kansei design group represent the design value of the product. The criteria in the design for supply chain group represent the supply chain and manufacturing cost of the product. It is required to evaluate the design value and the supply chain cost to determine the final design. For the purpose of evaluating the criteria in the three criteria groups, a fuzzy analytic network process (FANP) method is presented to evaluate a weighted index by calculating the total relational values among the three groups. A method using the technique for order preference by similarity to ideal solution (TOPSIS) is used to compare and rank the design alternative cases according to the weighted index using the total relational values of the criteria. The final decision of a design case can be determined by using the ordered ranking. For example, the design case with the top ranking can be selected as the final design case. Based on the criteria in the evaluation, the design objective can be achieved with a combined and weighted effect of the design value and manufacturing cost. An example product is demonstrated and illustrated in the presentation. It shows that the design evaluation model is useful for integrated evaluation of functional design, Kansei design, and design for supply chain to determine the best design case and achieve the design objective.

Keywords**—**Design evaluation, functional design, Kansei design, supply chain, design value, manufacturing cost, fuzzy analytic network process, technique for order preference by similarity to ideal solution.

I. Introduction

IN a product life cycle, to design a product with a given product requirement and design objective, there can be alternative decisions to determine and assign the detailed specifications of the components and parts. For example, for a mechanical product, the components and parts can be designed with different geometric shapes, sizes, and dimensions. Likewise, if given the required material property of a component, different materials can be selected and manufactured with detailed processing, operation, and finishing. With the concept, the detailed specifications such as geometric shape, sizes, dimensions, material, manufacturing processes, operations, and finishing can be assigned and selected to propose the feasible alternative design cases. In this way, in the design modeling stage, the design alternative cases can be proposed to fulfill the design requirement and achieve the design objective.

After the design modeling stages, in the design evaluation stage, it is required to evaluate the design alternative cases to decide and select the final design case. Given the different design specifications in the design cases, the components need to be manufactured with different manufacturing processes. If the manufacturing processes are different, the supply chain will be affected. Therefore, the effects of using the different design cases on the supply chain need to be evaluated using a sysmatic method.

In the previous research, the problems of supplier selection and design for supply chains have been modeled and solved with different approaches and methods. In the research of [1], the criteria of forward design, reverse design, and supply chain in a closed-loop design model were analyzed using a fuzzy analytical network process method. A product development model by considering green logistics to evaluate design, manufacturing, and green supply chain has been presented in [2]. In the research [2], the related literature in closed-loop supply chain research was investigated and reviewed. The research in [3]-[5] presented the methods for supplier evaluation and selection with different evaluation criteria. The research in [6] presented a literature review and a model of supply chain performance measurement.

In the recent development of product design, the major objectives that commonly targeted are functional design and Kansei design. The functional design is the primary objective that a product is created and modeled. The function design determines how a product can be used to work and perform functions. On the other hand, the Kansei design objective can be categorized as the factors that attract people with the visual effects, usability, or emotional effects. The three objectives can be analyzed based on value and cost. The design value of a

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product can be represented by the criteria in the functional design group and Kansei design group. The manufacturing cost of a product can be represented by the criteria in the design for supply chain group which describing the manufacturing activities for producing and delivering the product.

In this research, the purpose is to develop an analytical model for evaluating the alternative design cases to make decision for final production. The evaluation criteria are functional design, Kansei design, and design for supply chain. In the functional design group, the criteria include primary function, expansion function, improved function, and new function. In the Kansei design group, the criteria include geometric shape, dimension, surface finish, and layout. In the design for supply chain group, the criteria include material, manufacturing process, assembly, and supply chain operation. Since value and cost are two main factors for developing a product, it is required to evaluate the design alternative cases according to the design value and the manufacturing cost in order to determine the final design case.

In order to evaluate the criteria in the three criteria groups, a fuzzy analytic network process (FANP) method [7] is developed to formulate a weighted index among the three groups. The output total relational values of the design alternative cases are described using the weighted index. For the purpose of selecting a design case, a method using the technique for order preference by similarity to ideal solution (TOPSIS) [8] is developed to compare and rank the weighted index of the alternative design cases. The idea is to use the weights or the combined effects of the criteria in the three groups to evaluate and select the design alternative cases.

With the above methods, the design alternative cases can be evaluated and ranked according to the weighted index using the total relational values of the criteria. A common decision rule is to select the design case with the top ranking as the final design case. Based on the evaluation and ranking, the design objective can be achieved with the highest design value or the lowest manufacturing cost, or a combination of the value and cost. By developing the design evaluation model in this research, product design not only satisfies the customers' aspects of Kansei and functional needs but also satisfies the objectives of design for manufacturing and supply chain. The alternative design cases can be evaluated by considering the three objectives in the design evaluation stage. In this way, the best design case can be determined.

Based on the above discussion, in order to make a complete evaluation of the design alternative cases, three groups of design criteria are constructed to evaluate the design cases. The relationships among the three groups are shown in Fig. 1. The criteria in the three groups are shown in Fig. 2.

In this research, the fuzzy analytic network process method is presented for evaluating the relationships among the design alternative cases. The model can be used to evaluate the relationships among the three groups. A weighted index can be formulated and calculated for selecting a design case.

The output total relational values describe the weights or the weighted indices describing the combined effects of the criteria in the three groups. Subsequently, the technique for order preference by similarity to ideal solution is used to compare and rank the alternative design cases. The weights or the weighted indices of the criteria in the three groups are utilized to evaluate and select the design alternative cases.

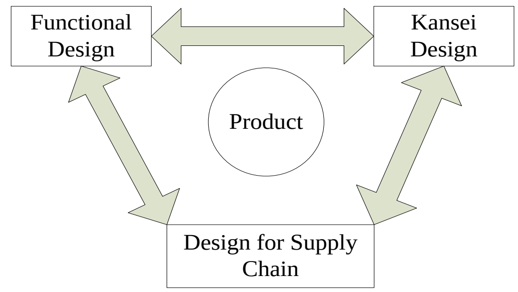

Fig. 1 The three groups of criteria in the design evaluation model

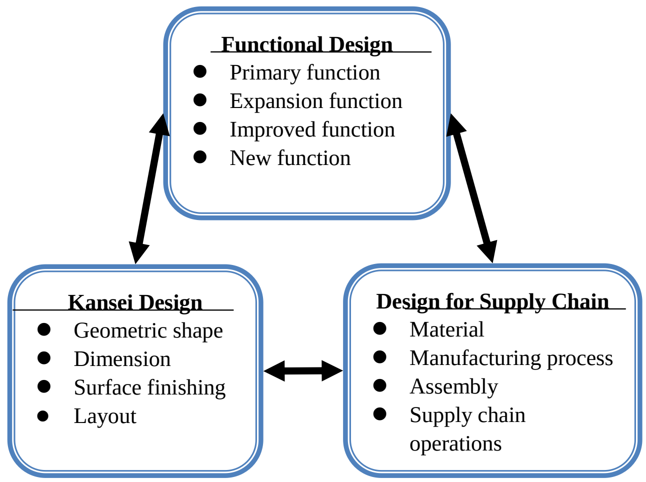

Fig. 2 The interactive relationships of the criteria in functional design, Kansei design, and design for supply chain

In this research, the main contribution lies in the new concept of a design evaluation model. Furthermore, this paper modeled the criteria of the three groups for an integrated evaluation of functional design, Kansei design, and design for supply chain to achieve the design objective with a higher design value or a lower manufacturing cost. The presented evaluation model has been implemented and tested with several example products. The results show that the presented methods and models are useful. It can be considered an effective model for solving the integrated evaluation problem. In this paper, the test results of an example product are presented and discussed.

The paper is organized as follows. Chapter I presents an introduction and a literature review. In Chapter III, the fuzzy analytic network process methods and the technique for order preference by similarity to ideal solution evaluation models are described. In chapter III, the application of the model is demonstrated and discussed. Finally, a conclusion is presented in Chapter IV.

II. Research Methods and Evaluation Models

In this chapter, the evaluation models using the fuzzy analytic network process and the technique for order preference by similarity to ideal solution are presented to evaluate the relationships among functional design, Kansei design, and design for supply chain. The design value can be represented by the criteria in the functional design and Kansei design groups. The supply chain cost can be represented by the criteria in the design for supply chain group.

A hierarchical structure is developed to represent he criteria in the three groups as shown in Fig. 2. The evaluation criteria are summarized as follows:

1) Functional design: primary function, expansion function, improved function, and new function.
2) Kansei design: geometric shape, dimension, surface finishing, and layout.
3) Design for supply chain: material, manufacturing process, assembly, supply chain operations.

A hierarchical structure is development to link the criteria in the three groups. The comparison matrices are modeled as fuzzy relational matrices. The matrices for evaluating the relationships between the pairs of the criteria among the three groups are created. The relational values of the criteria in the three groups can be calculated. Based on the calculation and observation, a higher relational value represents a higher interactive effect and relationship.

The model and formulation of the fuzzy analytic network process model are described as follows.

1) Create design cases. In the design stage, the detailed specifications can be modeled to create alternative design cases.
2) Create relational matrix of the functional design criteria for the design alternative cases. The functional design criteria are listed in Table I. The relational matrix of the functional design criteria of the design cases as shown in Table II.
3) Create relational matrix of the Kansei design criteria for the Kansei design activities. The Kansei design criteria are listed in Table III. The relational matrix of the Kansei design criteria of the design cases as shown in Table IV.
4) Create relational matrix of the design for supply chain criteria for the design for supply chain activities. The design for supply chain criteria are listed in Table V. The relational matrix of the design for supply chain criteria of the design cases as shown in Table VI.
5) The notations in the tables are as defined as follows.
   α : Set of components in design cases
   β : Set of components in design cases
   $p_{\alpha i}$: Components in design cases
   $p_{\beta i}$: Components in design cases
6) Develop comparison matrix between the criteria of the three groups of functional design, Kansei design, and design for supply chain, as shown in Table VII.
7) Perform pair-wise comparison with evaluation values provided by the users.

$$A_{ij} = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1p} \\ a_{21} & 1 & a_{23} & \cdots & a_{2p} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{p1} & a_{p2} & a_{p3} & \cdots & 1 \end{bmatrix} \quad (1)$$

A_{ij} represnets the matrix of j criterion in i group, where a_{mn} represents the n evaluation value of m criterion with p number of criteria.

$$a_{nm} = 1/a_{mn} \;, \quad \forall \;\; m,n = 1,2,..., p.$$

8) Perform a check of consistency of the evaluation values using consistency index ($C.I.$).
9) Create the fuzzy relational matrix.

$$\tilde{A}_{ij} = \left[\tilde{a}_{mn}\right] = \begin{bmatrix} 1 & \tilde{a}_{12} & \tilde{a}_{13} & \cdots & \tilde{a}_{1p} \\ \tilde{a}_{21} & 1 & \tilde{a}_{23} & \cdots & \tilde{a}_{2p} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{p1} & \tilde{a}_{p2} & \tilde{a}_{p3} & \cdots & 1 \end{bmatrix} \quad (2)$$

where l_{mn}: The left value of the fuzzy number of n evaluation value of m criterion. a_{mn}: The middle value of the fuzzy number. u_{mn}: The right value of the fuzzy number.

TABLE I
FUNCTIONAL DESIGN CRITERIA

F_1	F_2	F_3	F_4
Primary function	Expansion function	Improved function	New function

TABLE II
RELATIONAL MATRIX OF FUNCTIONAL DESIGN CRITERIA

	α	β	Relational value			
			F_1	F_2	F_3	F_4
Design Case	$p_{\alpha i}$	$p_{\beta 1}$				
		$p_{\beta 2}$				
		$\vdots$				
		$p_{\beta i}$				
		Sum				
		Average				

TABLE III
KANSEI DESIGN CRITERIA

K_1	K_2	K_3	K_4
Geometric shape	Dimension	Surface finishing	Layout

TABLE IV
RELATIONAL MATRIX OF KANSEI DESIGN CRITERIA

	α		Relational value			
		β	K_1	K_2	K_3	K_4
Design Case	$p_{\alpha i}$	$p_{\beta 1}$				
		$p_{\beta 2}$				
		$\vdots$				
		$p_{\beta i}$				
		Sum				
		Average				

TABLE V
DESIGN FOR SUPPLY CHAIN CRITERIA

S_1	S_2	S_3	S_4
Material	Manufacturing process	Assembly	Supply chain

TABLE VI

RELATIONAL MATRIX OF DESIGN FOR SUPPLY CHAIN CRITERIA

	α	β	Relational value S_1	S_2	S_3	S_4
Design Case	$p_{\alpha i}$	$p_{\beta 1}$				
		$p_{\beta 2}$				
		$\vdots$				
		$p_{\beta i}$				
		Sum				
		Average				

10) Calculate de-fuzzy evaluation numbers using the center of gravity de-fuzzy method.

$$DF_{mn} = \frac{(l_{mn} + a_{mn} + u_{mn})}{3} \tag{3}$$

where DF_{mn}: De-fuzzy weighted relational value.

11) Calculate the final relational values between the criteria of the three groups as shown in Table VII.

$$PV_{[j]m} = \sum_{n=1}^{N}\left(\frac{DF_{[j]mn}}{\sum_{m=1}^{M} DF_{[j]mn}}\right)\Bigg/ N \tag{4}$$

12) Model the super matrix as shown in Table VIII. The presented matrix model can be applied to analyze and evaluate the interactive relationships in the three models of functional design, Kansei design, and design for supply chain. In the design evaluation, the model can be applied to evaluate the design cases by using the relational values.

TABLE VII
THE COMPARISON MATRIX AND RELATIONAL VALUES OF THE FANP MODEL

		Functional Design F_1	..	F_4	Kansei Design K_1	..	K_4	Design for Supply Chain S_1	..	S_4
Functional Design	F_1									
	...									
	F_4									
Kansei Design	K_1									
	...									
	K_4									
Design for Supply Chain	S_1									
	...									
	S_4									

Given the evaluation values of the design cases, the technique for order preference by similarity to ideal solution can be applied to evaluate the design cases for decision-making. The model is described as follows:

1) Create the matrix of evaluation values of the criteria of the design cases.

$$B = m \times n$$

$$B = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_m \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mn} \end{bmatrix} \tag{5}$$

B_m: design case m,

b_{mn}: evaluation value of n criterion of design case m.

TABLE VIII
THE SUPER MATRIX OF DESIGN CASES USING THE FANP MODEL

Design case evaluation		Design Case 1	Design Case 2	Design Case 3	Design Case m	Design Case M
Functional design	Primary function	Values	…			
	Expansion function	…				
	Improved function					
	New function					
Kansei Design	Geometric shape	Values	…			
	Dimension	…				
	Surface finishing					
	Layout					
Design for Supply Chain	Material	Values	…			
	Manufacturing process	…				
	Assembly					
	Supply chain operation					

2) Calculate normalized evaluation value R.

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} & \cdots & r_{1n} \\ r_{21} & r_{22} & r_{23} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & r_{m3} & \cdots & r_{mn} \end{bmatrix} \tag{6}$$

$R = (r_{ij})_{m\times n}$: matrix of normalized evaluation values.

$$r_{ij} = b_{mn} \Big/ \sqrt{\sum_{i=1}^{m} b_{ij}^{\;2}}\,,\; i = 1,2,\cdots,m,\; j = 1,2,\cdots,n \text{ 。}$$

r_{ij} :normalized evaluation value of criterion r in design case i,

3) Calculate weighted normalized evaluation values.

$$V_{ij} = (v_{ij})_{m\times n} = (w_j r_{ij})_{m\times n},\; i = 1,2,\ldots,n\,. \tag{7}$$

V_{ij} ：weighted normalized evaluation value of criterion r in design case i,

$$w_j = W_j \Big/ \sum_{j=1}^{n} W_J\,,\; j = 1,2,\ldots,n\,\cdot \tag{8}$$

where $\sum_{j=1}^{n} w_j = 1$, the weight w_j is obtained from the output of the FANP in the previous model.

4) Determine ideal solution B^+ and negative ideal solution B^-.

$$
\begin{aligned}
B^+ &= \{(maxV_{ij} \mid j \in J), (minV_{ij} \mid j \in J) \mid i = 1,2,\ldots m\} \\
&= \{v_1^+, v_2^+, \ldots, v_n^+\} \\
B^- &= \{(minV_{ij} \mid j \in J), (maxV_{ij} \mid j \in J) \mid i = 1,2,\ldots m\} \\
&= \{v_1^-, v_2^-, \ldots, v_n^-\}
\end{aligned} \tag{9}
$$

where $J = \{ j = 1,2,\ldots,n \mid j$ positive relational effect$\}$;
$J = \{ j = 1,2,\ldots,n \mid j$ negative relational effect$\}$

5) Calculate separation of positive and negative solutions.

$$S^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2} \tag{10}$$

$$S^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \tag{11}$$

6) Calculate similarity.

$$D_i = \frac{S_i^+}{S_i^+ + S_i^-}, \; 0 \leqq D_i \leqq 1. \tag{12}$$

The values of D_i can be used to evaluate the design cases. The values of D_i can be ranked in a descending order. The design case with a larger D_i value can be determined as a good design case according to the criteria. For example, in the following example with 8 design cases, the design case D_8 can be decided as the best design case. The preference order of the design cases can be decided as indicated in the ranked descending order: $D_8 > D_9 > D_1 > D_4 > D_2 > D_{10} > D_5 > D_6 > D_7 > D_3$.

III. Application to Evaluation of Design Cases Using the Models

In this paper, the developed models have been implemented and tested. In this presentation, the basic shape of a notebook computer is used as an example product. The example product as shown Fig. 3 has also been used as the example in [1]. Given the alternative design cases, in the design evaluation stage, a design case with a desired evaluation value can be selected as the final design case.

IV. Conclusions

In this research, a model for evaluating design cases by modeling and evaluating the criteria in functional design, Kansei design, and design for supply chain is presented. The criteria in the functional design and Kansei design represent design values. The criteria in the design for supply chain group represent costs. The fuzzy analytic network process method is developed for integrated evaluation of the criteria in the three models. The technique for order preference by similarity to ideal solution is applied to evaluate the design cases by ranking the preferences of the design cases. The presented model can be used to select the better or the most suitable design cases according to the cost and value criteria. In the research, the models have been tested with example products. In this presentation, an example product is illustrated and demonstrated. The test results show that the model is useful for integrated evaluation of functional design, Kansei design, and design for supply chain. Future research can be directed to investigate more practical criteria related to costs and values.

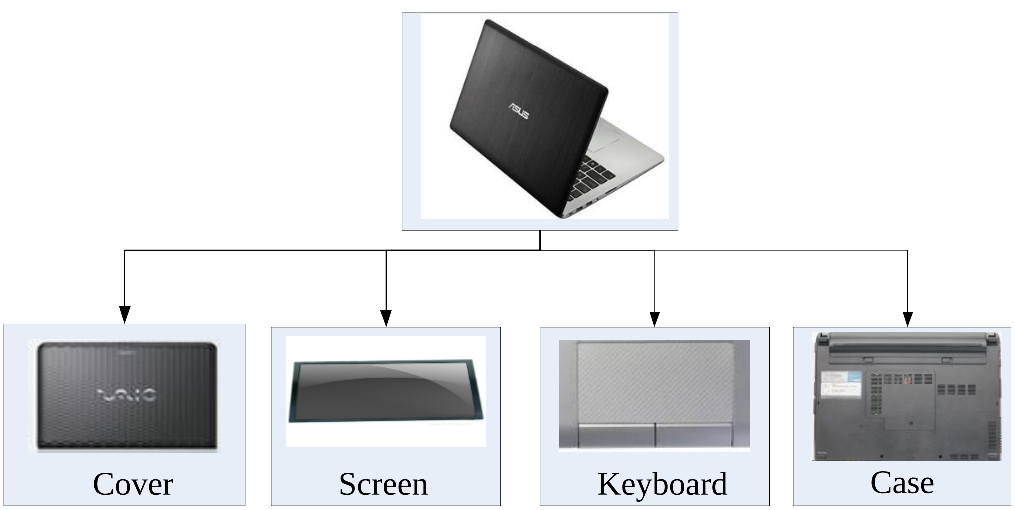

Fig. 3 A notebook computer is used as the example product for testing and demonstration

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