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Evaluation and decision of products conceptual design schemes based on customer requirements †

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Abstract

Within the competitive market environment, understanding customer requirements is crucial for all corporations to obtain market share and survive competition. Only the products exactly meeting customer requirements can win in the market place. Therefore, customer requirements play a very important role in the evaluation and decision process of conceptual design schemes of products. In this paper, an evaluation and decision method based on customer requirements is presented. It utilizes the importance of customer requirements, the satisfaction degree of each evaluation metric to the specification, and an evaluation metric which models customer requirements to evaluate the satisfaction degree of each design scheme to specific customer requirements via the proposed BP neural networks. In the evaluation and decision process, fuzzy sets are used to describe the importance of customer requirements, the relationship between customer requirements and evaluation metrics, the satisfaction degree of each scheme to customer requirements, and the crisp set is used to describe the satisfaction degree of each metric to specifications. The effectiveness of the proposed method is demonstrated by an example of front suspension fork design of mountain bikes.

Keywords: Conceptual design; Customer requirement; Evaluation and decision method; Fuzzy reasoning

1. Introduction

In the conceptual design process of products [1, 2], designing products to meet the demands of the market is the main intention of evaluating conceptual design schemes of products. Due to the essential characteristics of the market, customer requirements must be considered in order to meet the needs, so as to occupy the market. Therefore, in the evaluation and decision process of conceptual design schemes of products, customer requirements must be treated as an important element. Since designed products are based on the evaluation and decision process of the conceptual design schemes, they exactly meet customer needs. Hence, the production efficiency and profit of company will be further improved.

The relationship among customer requirements, market, evaluation and decision of conceptual design schemes of products is described in Fig. 1, where the arrows represent the information flow across the different design phases and aspects.

The remainder of this paper is structured as follows. Section 2 reviews customer requirements. Section 3 develops the evaluation and decision methods of the conceptual design schemes of products based on customer requirements. An example is given in Section 4 to illustrate the proposed method, and it is followed by a conclusion in Section 5.

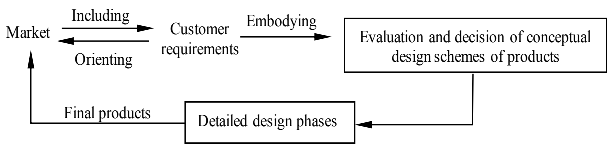

Fig. 1. Relations among customer requirements, market and evaluation and decision of conceptual design schemes of products.

2. Customer requirements

Due to its importance in the evaluation and decision process of the product conceptual design schemes, customer requirements are reviewed in this section.

2.1 Acquiring customer requirements

The research on customer requirements is a new subject between behavioral science and social science [3], and it consists of investigation of consumption mood and behavior, the

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method of how to make the relations among designers, producers and customers compatible. The details research directions in this area are as follows [4]:

(1) Market and customer survey. The main information to be surveyed includes customer information, market information, technology information, economy information, and products specification information etc. Based on the aforementioned information, the products which meet customer requirements will be produced. For example, many of the ideas of IBM's outstanding products came from the purchasers and users.

(2) Transformation from the technology perspective to the market perspective. It mainly contains following points: designing products based on the market needs, and adopting customer requirements, etc.

(3) Discerning customer clusters and distinguishing the market. The factors to be considered include consumption mood, consumption behavior, economic conditions, and geography/environment etc.

(4) Designing products from the perspective of customers. Corporations should develop their management based on customers' ideas, but not the ideas from themselves.

Based on these methods, customer requirements can be understood properly, and the products that can meet customer requirements will be designed.

2.2 Dynamic characteristics of customer requirements

The customer requirements in most aforementioned research are treated from the static viewpoint. Customer requirements are considered only in a specific time. In reality, customer requirements might change over time. Therefore, if dynamic behaviors of customer requirements are not taken into account in evaluating the conceptual design schemes of products, the final result may not be acceptable [5].

The dynamic characteristic of customer requirements is very important, and it provides an effective method to understand the nature of customer requirements. A customer requirement could be described as a customer requirement curve changing along the time axis. Generally, this curve increases gradually with time, but may suffer a sudden jump when a special event occurs. See, for example, Fig. 2.

The reasons for customer requirements changing with time can be summarized as follows:

(1) The recognition of products by customers is a gradual process.

(2) Since some characteristics of the product might improve greatly within a short time because of application of new technologies, customer requirements are also improved by the new technologies within a short time.

(3) Since the quality of life decreases due to the deterioration of politics, economy, and environment etc., customer requirements also descend with respect to these negative events.

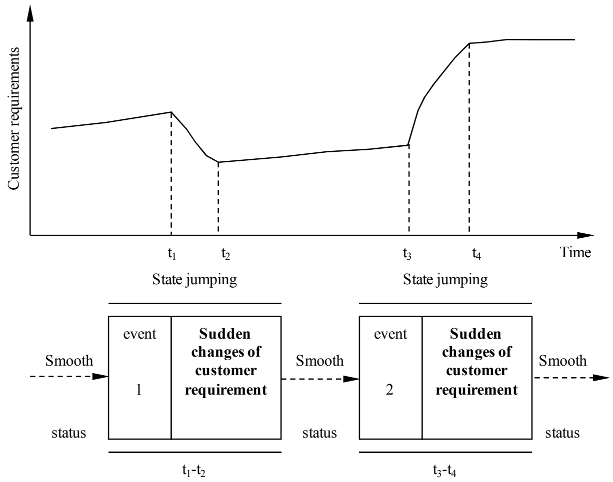

Fig. 2. Dynamic characteristic of customer requirements [6].

2.3 Prediction of customer requirement

Because of the dynamic characteristic of customer requirements, it is necessary to predict how they will change in the future after customer requirements are obtained in the evaluation and decision process of conceptual design schemes of products. Since customer requirements predictions are used to evaluate the conceptual design schemes of products, a reasonable result can be obtained.

In general, two methods are used to predict customer requirements [6]:

(1) Qualitative prediction. Customer requirements are predicted based on former experience. The methods of qualitative prediction include the expertise method, probability method, foreground analysis method, and conformation analysis method etc.

(2) Quantitative prediction. The qualitative methods are transformed into the quantitative ones based on market survey. Hence, the final result can be obtained through mathematical methods.

The quantitative prediction method can be further classified into the time prediction method and cause-effect prediction method:

(1) Time sequence prediction method. This method is determined according to the rule that a phenomenon changes with time to predict customer requirements. Methods belonging to this classification include the shift average method, index smoothing method, and regression analysis method.

(2) Cause-effect prediction. This method is determined according to the rule that some phenomenon changes with the other phenomena to predict customer requirements. The correlation regression analysis method and the devotion and output method etc., are these belonging to this group.

In the practical prediction process, these method are interrelated and can be used together to predict customer requirements.

Fig. 3 demonstrates the prediction process of customer re-

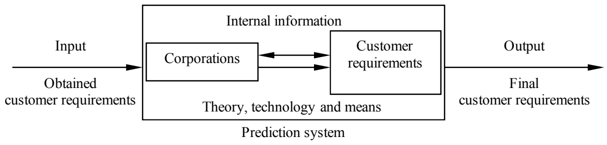

Fig. 3. Prediction process of customer requirements.

quirements after getting the customer requirements [7], where the internal information is the information flow during analyzing the customer requirements.

Therefore, it is important that corporations should put emphasis on the research of customer requirements and understanding the dynamic nature of customer requirements in order to obtain objective customer requirements. The aforementioned methods and their combination can be used to characterize the dynamic behavior of customer requirements, but this is not within the scope of this paper.

2.4 Data analysis of customer requirements

After obtaining the customer requirements from various means including prediction, it is necessary to combine all this information into a unified customer requirement.

From the life cycle point of view, customer requirements can be divided into four phases: customer consultation phase, product purchase phase, product consumption phase, and product rejection phase [8]. Customers have their special requirements corresponding to each phase. In the customer consultation phase, customers provide their personal information, such as job, income, and hobby. Corporations then build a personal information database. At the same time, corporations also build a product consultation expert knowledge system and open the system to customers hierarchically according to degree of secrecy. In the product purchase phase, customer requirements can be standardized into function requirements, characteristics, appearance, and price. In the product consumption phase, customer requirements mainly contain reliability, usage life, and technology. In the product disposal phase, customer requirements include product value evaluation and product upgrading.

2.5 Method of calculating weights of customer requirements

When the final customer requirements are obtained, weights should be calculated in order to evaluate the conceptual design schemes of products. However, for some customer requirements, if they result in small differences between each conceptual design scheme, it can be confirmed that they have a minor impact on the evaluation and decision process of conceptual design schemes of products. On the other hand, for some customer requirements, if they result in significant differences in each conceptual design scheme of products, it indicates that they play an important role in the evaluation and decision process of conceptual design schemes of products. In other words, the importance of each customer requirement is associated with how different each conceptual design scheme of the products may change with respect to the requirement. Therefore, it is necessary to eliminate those customer requirements that have slight or insignificant impact on each conceptual design scheme of products. Moreover, eliminating the unimportant requirement can further reduce the complexity of computing the weights of customer requirements and improving the computational efficiency. Methods, like statistical sensitivity analysis, can be used to realize this purpose [19]. In this paper, the Analytical Hierarchy Process (AHP) [9] together with the pairwise comparison is utilized to calculate the weights of customer requirements.

The judgment matrix is a matrix obtained through the pairwise comparison of customer requirements. According to the literature [9, 17], a necessary and sufficient condition for satisfactory consistency of a matrix is that the principal eigenvalue of the matrix equals to n, the order of the matrix. As proved in [17], if a matrix A is consistent, one has $\lambda_{\max} = n$ since only one eigenvalue is nonzero and the sum of eigenvalues equals to the trace of the matrix. However, due to the errors from judgment, a small perturbation around a simple eigenvalue may lead to an eigenvalue problem that the matrix is no longer consistent. Such inconsistency can be characterized by the consistency ratio (CR) which is defined as

$$CR = \frac{CI}{RI} \quad (1)$$

where CI is defined as

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

where $\lambda_{\max} - n$ is the sum of eigenvalue leaving out the maximum eigenvalue. The smaller *CI* indicates the greater satisfactory consistency the matrix possesses. *RI* in Eq. (1) is the random index which is used to modify the value of *CR*. The value of *RI* can be chosen based on *n*, the order of matrix, as shown in Table 1 [18].

Table 1. Values of random index RI.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

CR provides a very good estimation of the satisfactory consistency of judgment. If *CR* of the judgment matrix is less than 0.10, the degree of satisfactory consistency of the matrix is acceptable. However, if the matrix is not acceptable, it is necessary to adjust the elements of the matrix in order to generate a new matrix which is acceptable in terms of satisfactory consistency. Computing these weights of customer requirements is not an efficient process, and the new matrix may not possess satisfactory consistency either. Therefore, in this work, a new method to modify the matrix is introduced.

In fact, the vector that is scaled to the range between 0 and

1 from each row element of the judgment matrix is the approximated weight of each customer requirement. Therefore, n rows of a judgment matrix with n orders could be considered as the n compositor result of importance for all customer requirements. The *judgment consistency* of a matrix is defined as the property in which ranking of the entries of the n column vectors within the matrix is the same [10]. When the judgment matrix possesses judgment consistency, it means that the judgments from experts are overall not conflicting. Hence, the judgment consistency of the matrix can be considered as a standard to decide whether a matrix is acceptable.

The conclusion can be drawn as follows: when a matrix does not possess satisfactory consistency, its judgment consistency should be analyzed. If this matrix does not have judgment consistency, it is necessary to adjust its elements again in order to generate a new matrix. If this matrix has judgment consistency, there is no need to further adjust its elements again, and the matrix can be modified by the method below:

Let $A=(a_{ij})_{n\times n}$ represent the original matrix which does not have the satisfactory consistency, and the new generated matrix is called $B=(b_{ij})_{n\times n}$. B satisfies

$$b_{ij}=\begin{cases}\frac{1}{n}\sum_{k=1}^{n}a_{ik}a_{kj} & i<j\\ 1 & i=j \quad (i,j=1,2,\cdots,n)\\ 1\Big/(\frac{1}{n}\sum_{k=1}^{n}a_{ik}a_{kj}) & i>j.\end{cases} \tag{3}$$

In matrix A, a_{ij} is the importance ratio of the ith customer requirement and the *j*th customer requirement; and $a_{ik}a_{kj}$ is the indirect importance ratio of the *i*th customer requirement and the *j*th customer requirement based on the *k*th customer requirement, then $\frac{1}{n}\sum_{k=1}^{n}a_{ik}a_{kj}$ is the average value of the importance ratio of the *i*th customer requirement and *j*th customer requirement based on each customer requirement.

In practical application, the consistency of the judgment matrix will be improved by applying the modifying method provided above. An example is given below to verify the validity of this method.

For example, suppose a matrix A

$$A=\begin{bmatrix}1 & 8 & 9\\ 1/8 & 1 & 8\\ 1/9 & 1/8 & 1\end{bmatrix}. \tag{4}$$

It is easy to see that A has the judgment consistency, and its max eigenvalue $\lambda_{A\max}$ equals to 3.267, and its $CR(A)$ is 0.257>0.1. Hence, matrix A does not have satisfactory consistency.

The result of modifying matrix A based on the method presented above is expressed as B

$$B=\begin{bmatrix}1 & 137/24 & 82/3\\ 24/137 & 1 & 137/24\\ 3/82 & 24/137 & 1\end{bmatrix}. \tag{5}$$

The associated max eigenvalue $\lambda_{B\max}$ is 3.0034<3.257, and its $CR(B)$ is 0.003<0.1. Therefore, B possesses satisfactory consistency. It indicates that the satisfactory consistency of matrix A has been improved.

In addition, if the matrix has both satisfactory consistency and judgment consistency, it illustrates that the final eigenvector, i.e., the final weight of each customer requirement calculated from the matrix, is acceptable.

However, it is necessary to take into account that a matrix should not be treated as useless if it has neither satisfactory consistency nor judgment consistency. For example, C is given as follows:

$$C=\begin{bmatrix}1 & 3 & 1/4 & 1/3\\ 1/3 & 1 & 1/5 & 3\\ 4 & 5 & 1 & 5\\ 3 & 1/3 & 1/5 & 1\end{bmatrix}. \tag{6}$$

One has $\lambda_{C\max}$ is 5.0765, and its $CR(C)$ is 0.403>0.1. Hence, C has neither satisfactory consistency nor judgment consistency since the value of CR is greater than 0.1 and the rankings of the entries of the four column vectors are not identical. The judgment result of the four rows of entries in C is inconsistent.

However, since it is not difficult to show that the values of entries in the third row are the largest one in each column, the conclusion can be drawn from matrix C as below: the third customer requirement is the most important among all customer requirements. Therefore, a new matrix should be generated based on the aforementioned rules.

2.6 Design process using customer requirements

After acquiring customer requirements, the aforementioned prediction method in Section 2.3 will be used to predict the variation of customer requirement. These requirements will be used to evaluate the conceptual design schemes of products. The importance of customer requirements should be computed by AHP before evaluation and decision. On the other hand, the evaluation and decision process of the conceptual design schemes of products and the evaluation metrics of the specifications corresponding to customer requirements are also very important in the evaluation and decision process of conceptual design schemes. To express the relationship between customer requirements and evaluation metrics to obtain an objective and precise evaluation and decision result, it is very important to make standard customer requirements. The relationship between customer requirements and evaluation metrics can be built up based upon the customer requirement features. Fifteen

Table 2. Features and significance of customer requirements [19].

Customer requirement features	Content and significance of customer requirements
Energy	Type of energy (heat, electricity etc.); Status of energy; output; input; conversion; storage; consumption; efficiency
Material	Type of material (gas, liquid, solid); Status of material; input; output; flow; storage; conversion; character (intensity, tenacity, elasticity etc.)
Signal	Type of signal (light, sound, taste, humidity etc); input; output; conversion; control
Character	Size (height, length, thickness, position, diameter, clearance, tolerance etc.); collocation; connection; composition
Function	Type of function (acceleration, reliability etc.); Type of movement (lineal movement, rotary movement); kinematics; dynamics; load (direction, value, frequency); distortion etc.
Safety	Type (direct protection, indirect protection, signal and token of alarm; Environment safety; rules
Manufacture	Type (lathe, mill, dig, grind, grip etc.); establishment; assemblage
Quality	Control; protection (test, checkout)
Maintainability	Convenience; shortcut; service cycle; checkout; cleanliness; substitution
Profit	Investment; expenditure (manufacturing expenditure, tool expenditure); unit price
Plan	Date (discovery cycle, design, production, package, transportation)
Transportation	Type; method; transportation status
Aesthetics	Type; shape; color; surface shape etc.
Environment	Type; limited material; limited status; recycle

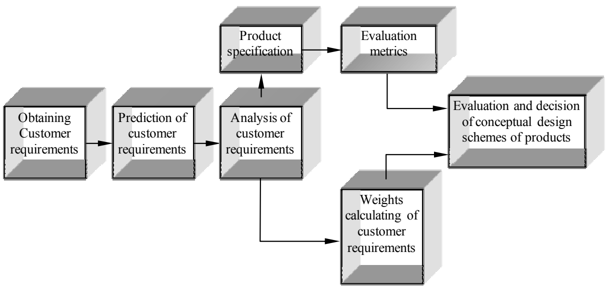

Fig. 4. Design process of customer requirements.

examples of the customer requirement features are summarized in Table 2 [11].

Here, the process containing the collection, prediction, and analysis of customer requirements is called the design process of customer requirements in the evaluation and decision process of conceptual design schemes. This process is described in Fig. 4.

The design of customer requirements is a sub-process of product exploitation in the life cycle. This process starts with a corporation acquiring customer requirements and ends up with the product requirement specification being generated. The design of customer requirements is the initial process in the life cycle of the product, and it acts as a bridge connecting the market and corporation.

In this process, corporations confirm their market and obtain the corresponding customer requirements firstly, then analyze them based on the existing design knowledge of products, and then generate the product requirement specification that describes the product features in detail. Through the analysis, it is easy to know that the design process of customer requirements is also very important in the evaluation and decision process of conceptual design schemes.

3. Evaluation and decision of conceptual design of products

The conceptual design is the first step in the overall process of product design. Insufficient evaluation of conceptual design schemes will impact the selection of conceptual design schemes. Inappropriate conceptual design scheme may eventually impact the function, reliability, and economy of the products [20, 21]. A method for evaluation and decision of conceptual design schemes of products based on customer requirements is presented herein, and it consists of four steps [12]:

(1) Collection of customer requirements and ranking their importance.

(2) Conversion between customer requirements and evaluation metrics, and establishing of their relationship.

(3) Initial evaluation and decision of conceptual design schemes based on the specification.

(4) Evaluation and decision making of the conceptual design schemes based on the satisfaction degree of each conceptual design scheme to customer requirements.

In the evaluation and decision process, fuzzy sets are used to describe the importance of customer requirements, the relationship between customer requirements, evaluation metrics, and the satisfaction degree of each scheme to customer requirements. A crisp set is used to describe the satisfaction degree of each evaluation metric to specification. Therefore, the importance of customer requirements, the relationship between customer requirements and evaluation metrics, together with the satisfaction degree of evaluation metrics to the specification are used to calculate the satisfaction degree of each conceptual design scheme. The conceptual design scheme with the highest satisfaction degree is the best scheme to be chosen.

3.1 Obtaining customer requirements and ranking their importance

Confirming customer requirements is the most important task in the evaluation and decision process of conceptual design schemes of products. Generally, customer requirements are expressed in qualitative language, like “the cost should be low” and “the appearance should look smart”. As mentioned earlier, after customer requirements are obtained, predicted and analyzed, they are used for evaluation and decision of conceptual design schemes of products. In this work, AHP is used to calculate the weights of customer requirements.

If n customer requirements are associated with n weights, $w_1, w_2, \cdots, w_n$, the relative importance a_{ij} is obtained as

$$a_{ij} = w_i / w_j . \tag{7}$$

The pair wise ratios satisfy

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} . \tag{8}$$

Since each customer requirement is as equally important to itself, the value of a diagonal element in the matrix is 1 $(a_{ii} = 1)$, and values of the elements in the upper triangle of the matrix are the reciprocal values of the elements in the lower triangle of the matrix. In other words, only $\frac{1}{2}n(n-1)$ comparisons are needed. For ease of explanation, this equation is described as

$$(A - nI)w = 0 \tag{9}$$

where I is a $n \times n$ identity matrix. From this equation, it is apparent that n is an eigenvalue of A, and w is an eigenvector for eigenvalue n.

The weights of customer requirements are scaled to the range between 0 and 1. The importance of customer requirements is a fuzzy concept and it cannot be described precisely. Hence, it is modeled in fuzzy sets [13]. In the present paper, four fuzzy sets have been developed for modeling the importance of customer requirements: (1) Not important, (2) Somewhat important, (3) Important, and (4) Very important, as shown in Fig. 5.

3.2 Conversion between customer requirements and evaluation metrics and establishing their relations

Since customer requirements are usually described by qualitative expression, they are difficult to use in the evaluation and decision of conceptual design schemes of products directly. Therefore, conversion of customer requirements into evaluation metrics becomes necessary.

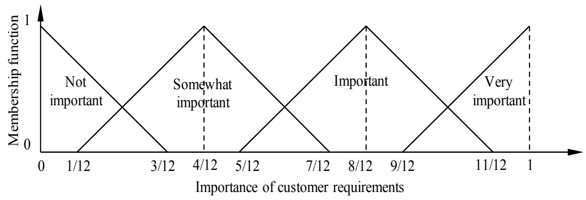

Fig. 5. Membership function of the importance of customer requirements.

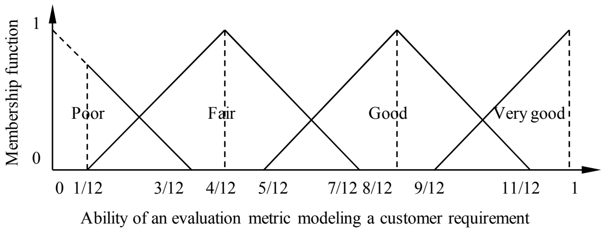

Fig. 6. Membership function of the ability of evaluation metrics modeling customer requirements.

In addition, to evaluate conceptual design schemes, it is necessary to know the quantitative relations between customer requirements and evaluation metrics, i.e., the ability of evaluation metrics modeling customer requirements. In this paper, their relationships are described by numbers between 0 and 1, where 1 indicates a perfect modeling ability to the customer requirements, whereas 0 indicates an impossible modeling ability to customer requirements. The relationships corresponding to the four fuzzy sets represent the ability of the evaluation metrics to model customer requirements: (1) Poor, (2) Fair, (3) Good, and (4) Very good, as shown in Fig. 6. It is noted that when the relationship is too weak (less than 1/12), the evaluation metrics cannot model a customer requirement properly.

3.3 Initial evaluation and decision of conceptual design schemes based on specification

A specification is used to evaluate evaluation metrics in the evaluation and decision process of conceptual design schemes of products. Each evaluation metric in the specification is usually described by a lower bound and an upper bound. Specification is developed based on customer requirements, competitive analysis of similar products, and product testing. Since the product specifications are associated with mandatory requirements from functional, structural, topology, safety, reliability, environmental, and economic aspects and must follow the industry standards, it can be characterized by crisp sets rather than fuzzy sets. Therefore, evaluation results are represented by conventional crisp sets, as shown in Fig. 7. A crisp set is considered as a special fuzzy set, where the value of membership function equals either 0 or 1.

Table 3. 32 fuzzy rules.

		Capability of evaluation metrics modeling customer requirements			
		Very good	Good	Fair	Poor
Evaluation metrics satisfy the specification					
Importance of customer requirements	Very important	Very good	Very good	Very good	Good
	Important	Very good	Very good	Good	Good
	Somewhat Important	Very good	Good	Good	Fair
	Not Important	Good	Good	Fair	Fair
Evaluation metrics do not satisfy the specification					
Importance of customer requirements	Very important	Very poor	Very poor	Very poor	Poor
	Important	Very poor	Very poor	Poor	Poor
	Somewhat Important	Very poor	Poor	Poor	Fair
	Not Important	Poor	Poor	Fair	Fair

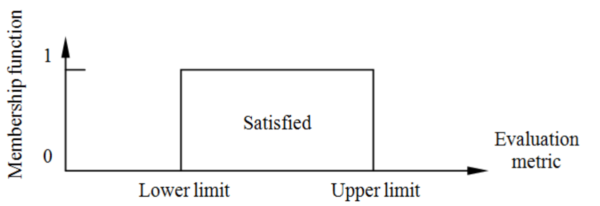

Fig. 7. Membership function of the satisfaction degree of evaluation metrics to specification.

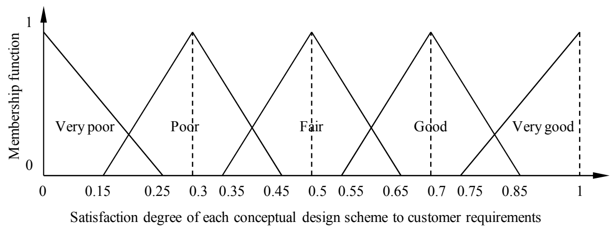

Fig. 8. Membership function of satisfaction degree of each conceptual design scheme to customer requirements.

3.4 Evaluation and decision of conceptual design schemes based on the satisfaction degree of customer requirements

Evaluation and decision of conceptual design schemes of products based on customer requirements is carried out as shown in Fig. 8 through using the previously mentioned measures:

(1) Importance of customer requirements

(2) Capability of evaluation metrics modeling customer requirements

(3) Satisfaction degree of evaluation metrics to specification

Satisfaction degree of each conceptual design scheme to customer requirements is also described by a number with value between 0 and 1. Five fuzzy sets are used to model this number: (1) Very poor, (2) Poor, (3) Fair, (4) Good, and (5) Very good, as shown in Fig. 8.

Then, fuzzy rules are developed for evaluating conceptual design schemes with the three measures mentioned above. The IF part of a fuzzy rule is composed of three expressions linked by logical-and (&), representing the fuzzy sets corresponding to the three measures. The THEN part of a fuzzy rule describes the fuzzy set representing satisfaction degree of conceptual design schemes to customer requirements. An example of the fuzzy rules could be "IF the conceptual design scheme SATISFIES the specifications AND the capability of evaluation metrics modeling customer requirements is VERY GOOD and the customer requirements is VERY IMPORTANT, THEN the satisfaction degree of the conceptual design scheme is VERY GOOD". Thirty-two fuzzy rules as shown in Table 3 are developed to represent the fuzzy relations for evaluation and decision of conceptual design schemes of products.

Each time, only one evaluation metric and one customer requirement is considered to evaluate a conceptual design scheme. The final evaluation and decision result considering all evaluation metrics and customer requirements is based on these individual results. For instance, when N customer requirements and M evaluation metrics are used in the evaluation and decision of conceptual design schemes of products, and suppose the result of evaluation and decision with considering the ith customer requirement and jth evaluation metric is described by S_{ij}, and the result of evaluation and decision considering the jth evaluation metric and all customer requirements is described by S_j, we have

$$S_j = \frac{1}{n_j}\sum_{i=1}^{n_j} S_{ij} \quad (j = 1,2,\cdots,M), \tag{10}$$

where, n_j ($n_j < N$) is the number of customer requirements in calculating S_j, and N is the number of customer requirements. Then the result of evaluation and decision considering all customer requirements and all evaluation metrics is obtained using

$$S = \frac{1}{M}\sum_{j=1}^{M} S_j . \tag{11}$$

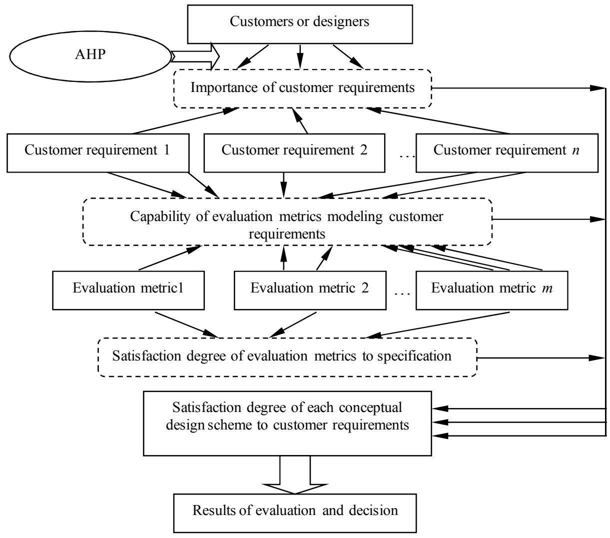

Fig. 9. Evaluation and decision of conceptual design schemes based on satisfaction degree of each conceptual design scheme to customer requirements.

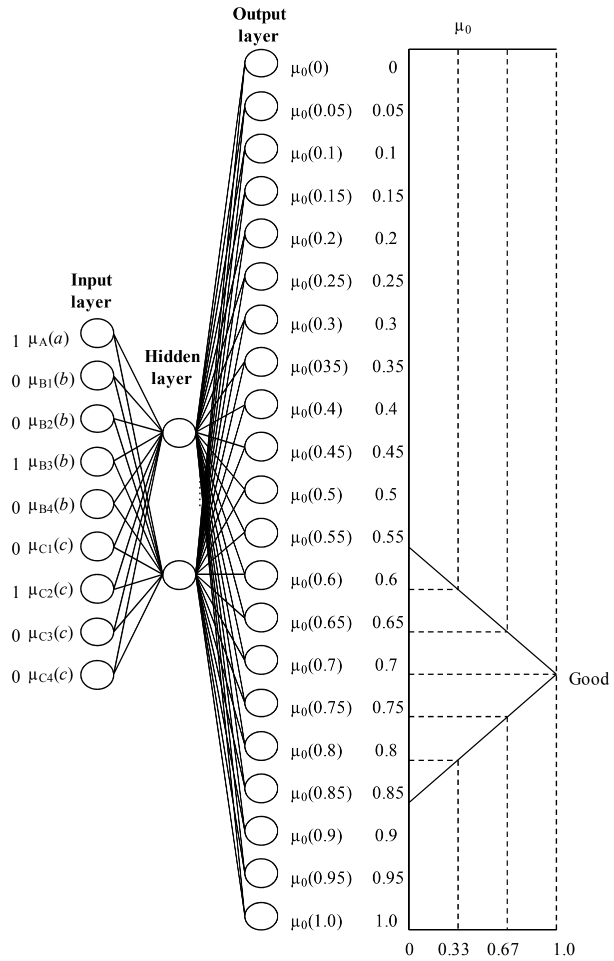

Fig. 10. BP Neural network for fuzzy reasoning to evaluate conceptual design schemes.

In addition, in the fuzzy reasoning process described as Fig. 9, a BP neural network is used in order to improve the calculating efficiency of fuzzy reasoning [14, 15]. The BP neural network utilized in this work, as shown in Fig. 10, has been developed for fuzzy reasoning to evaluate the conceptual design schemes of products. This BP neural network consists of three layers: an input layer, a hidden layer, and an output layer. The input layer has nine input nodes, representing the nine fuzzy membership functions (Figs. 5-7) used as antecedents of rules. These nine input nodes are organized in three groups, corresponding to the three input variables:

(1) Satisfaction degree of evaluation metrics to the specification,

(2) Capability of evaluation metrics modeling customer requirements,

(3) Importance of customer requirements.

The output layer has 21 nodes, representing the membership function of the fuzzy set to model the satisfaction degree of conceptual design schemes to customer requirements. In Fig. 10, one of 32 fuzzy rules, say "IF the evaluation metric SATISFIES the specification, and the evaluation metric has the ability to model the customer requirement and the customer requirement is SOMEWHAT IMPORTANT, THEN the conceptual design scheme is GOOD enough to satisfy the customer requirement," is expressed.

4. A case study

In this section, a case study of front suspension fork design of mountain bikes was used to demonstrate the effectiveness of the introduced method of evaluation and decision. The data provided in Ref. [16] was used for this study. Six different front suspension fork conceptual design schemes of mountain bikes were selected and evaluated based on the proposed method to identify the best one for further product development. One of these conceptual design schemes is shown in Fig. 11.

The evaluation and decision process for the best scheme was carried out in the following four steps.

Step 1: Obtaining customer requirements and ranking their importance.

As presented above, customer requirements were obtained through market research and customer research etc. For example, the designers or experts developed questionnaires on the front suspension fork of mountain bikes, and the contents of the questionnaires consisted of the ideas and thoughts of customers with regard to the front suspension fork of mountain bikes. The format of the questionnaires could contain choice, judgment, and essay questions.

In the mountain bike designs, six customer requirements were obtained by the corporation, as listed in Table 4.

The importance of customer requirements was identified through using the pairwise comparison method of the AHP by the designer or experts, and the final result is the average of results generated by designer or experts. The obtained importance matrix of customer requirements is shown in Table 5.

Table 4. List of customer requirements.

No.	Customer requirements
1	Reduces vibration to the hands
2	Allows easy traversal of slow, difficult terrain
3	Enables high speed descents on bumpy trails
4	Preserves steering characteristics of bike
5	Remains rigid during hard cornering
6	Light weight

Table 5. Importance matrix of customer requirements.

Customer requirements	1	2	3	4	5	6
1	1	6	1	4	5	3
2	1/6	1	1/6	1/2	1	1/3
3	1	6	1	4	5	3
4	1/4	2	1/4	1	3	1/4
5	1/5	1	1/5	1/3	1	1/3
6	1/3	3	1/3	4	3	1

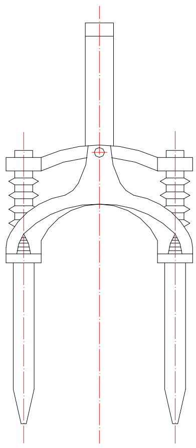

Fig. 11. Front suspension fork of mountain bike.

It can be shown that this matrix had judgment consistency. By calculation, it is also easy to show that the consistency ratio (*CR*) of this matrix was 0.11>0.1; hence the matrix does not have satisfaction consistency. Therefore, this matrix should be modified in the method mentioned previously. Suppose the new matrix is *B*.

$$B=\begin{bmatrix} 1 & \frac{17}{3} & 1 & \frac{121}{36} & \frac{19}{3} & \frac{17}{9} \\ \frac{3}{17} & 1 & \frac{131}{720} & \frac{3}{5} & \frac{13}{12} & \frac{41}{120} \\ 1 & \frac{720}{131} & 1 & \frac{121}{36} & \frac{19}{3} & \frac{58}{45} \\ \frac{36}{121} & \frac{5}{3} & \frac{36}{121} & 1 & 2 & \frac{31}{36} \\ \frac{3}{19} & \frac{12}{13} & \frac{3}{19} & \frac{1}{2} & 1 & \frac{59}{180} \\ \frac{9}{17} & \frac{120}{41} & \frac{45}{58} & \frac{36}{31} & \frac{180}{59} & 1 \end{bmatrix}. \quad (12)$$

Table 6. Calculated importance values of customer requirements.

Customer requirements	Importance of customer requirements
1	1.00
2	0.21
3	1.00
4	0.30
5	0.19
6	0.52

Table 7. Evaluation metrics.

No.	Evaluation metrics	Units
1	Attenuation from dropout to handlebar at 10 Hz	dB
2	Spring preload	N
3	Maximum value from the "Monster"	g
4	Minimum descent time on test track	s
5	Maximum travel (26 inch wheel)	mm
6	Rake offset	mm

Through calculation, it is easy to show that the eigenvalue of *B* was 6.08, and the consistency ratio (*CR*) of *B* was 0.016<0.1. Therefore, the new matrix *B* had satisfaction consistency. It is easy to show that the eigenvector of *B* was $(0.312, 0.056, 0.312, 0.099, 0.053, 0.168)$, and the elements of the eigenvector were scaled to the range between 0 and 1 for representing the importance of customer requirements. The obtained importance values of customer requirements are listed in Table 6.

Step 2: Conversion between customer requirements and evaluation metrics, and establishing their relations.

After the importance values of customer requirements were obtained, the customer requirements were then associated with evaluation metrics in order to enable the designers to understand the customer requirements in technical terms. The eight evaluation metrics developed for the front suspension fork design are summarized in Table 7. The "Monster" is a shock test used by Mountain Bike magazine.

The ability of evaluation metrics to model customer requirements can be obtained through the scores from designers or experts who are familiar with the front suspension fork of mountain bikes. Specifically, the experts or designers use the scoring method to determine the ability values of evaluation metrics to model customer requirements, and then calculate the averages of the ability values.

These values are listed in Table 8. The values represent the ability of evaluation metrics to model customer requirements. When a value is too small (less than 1/12), the evaluation metric cannot model the customer requirement properly. Therefore, it is impossible to evaluate the conceptual design schemes and the value was indicated by a blank as shown in Table 8.

Step 3: Initial evaluation and decision of conceptual design schemes based on specification.

The specification based on the eight evaluation metrics are shown in Table 9, and it is usually generated by the design engineers. Each evaluation metric is described by a lower bound and an upper bound.

Table 8. Capability of evaluation metrics modeling customer requirements.

Customer require-ments	Evaluation metrics							
	1	2	3	4	5	6	7	8
1	0.8		0.7	0.2				
2		0.6						
3	0.3		0.5	0.8				
4					0.2	0.4		
5		0.7					0.6	
6								1.0

Table 9. Specification.

Evaluation metrics	Units	Lower limits	Upper limits
1	dB	10.0	None
2	N	480.0	800.0
3	g	0	3.5
4	s	0	13.0
5	mm	33.0	50.0
6	mm	37.0	45.0

As mentioned above, six conceptual design schemes were selected for evaluation and decision. The values of evaluation metrics for the six conceptual design schemes are summarized in Table 10. When an evaluation metric satisfied the specification, the satisfaction degree value of evaluation metric to the specification was represented by 1, otherwise 0.

Step 4: Evaluation and decision of conceptual design schemes based on the satisfaction degree of each conceptual design scheme to customer requirements.

The evaluation and decision of conceptual design schemes was conducted by fuzzy reasoning using the BP neural network. For instance, when the fourth evaluation metric and the first customer requirement were used to evaluate the first conceptual design scheme, the three input variables and their corresponding nine fuzzy membership function values were calculated as shown in Table 11. These nine membership function values were used as the inputs for the trained BP neural network.

Each time, only one evaluation metric and one customer requirement were considered in evaluation and decision. The final evaluation and decision result considering all six customer requirements and the eight evaluation metrics was carried out based on these individual evaluation and decision results.

The outputs calculated from these nine membership function values mentioned above through the trained BP neural

Table 10. Conceptual design schemes and their evaluation metric values.

Evaluation metrics	Units	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6
1	dB	8.0[a]	15.0	10.0	15.0	9.0[a]	13.0
2	N	550.0	810.0[a]	500.0	710.0	480.0	680.0
3	g	3.6[a]	3.2	3.7[a]	3.3	3.7[a]	3.4
4	s	13.0	11.3	12.6	11.2	13.2[a]	11.0
5	mm	28.0[a]	48.0	43.0	46.0	33.0	38.0
6	mm	41.5	39.0	38.0	38.0	43.2	29.0[a]
7	kN/m	59.0[a]	110.0	85.0	85.0	65.0	130.0
8	kg	1.409[a]	1.385	1.409[a]	1.364	1.222	1.100

[a] Evaluation metrics that do not satisfy the specification.

Table 11. Input data considering the forth evaluation metric and the first customer requirement for the first conceptual design scheme.

Variable names	Variable values	Fuzzy sets	Membership functions
Satisfaction of the evaluation metric to the specification	1 (*a*)	Satisfied (μ_A)	1.00
Ability of the evaluation metrics modeling the customer requirements	0.2 (*b*)	Poor (μ_{B1})	0.20
		Fair (μ_{B2})	0.45
		Good (μ_{B3})	0.00
		Very good (μ_{B4})	0.00
Importance of the customer requirements	1.0 (*c*)	Not important (μ_{C1})	0.00
		Somewhat important (μ_{C2})	0.00
		Important (μ_{C3})	0.00
		Very important (μ_{C4})	1.00

Table 12. Evaluation and decision result of the first conceptual design scheme.

Customer requirements	Evaluation metrics							
	1	2	3	4	5	6	7	8
1	0.06		0.07	0.89				
2		0.66						
3	0.07		0.06	0.95				
4		0.72			0.33	0.68		
5							0.26	
6								0.06
Average values S_j	0.065	0.69	0.065	0.92	0.33	0.68	0.26	0.06

[a] Evaluation and decision value S=0.38.

Table 13. Evaluation and decision values of conceptual design schemes.

Evaluation metrics	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6
1	0.065[a]	0.935	0.935	0.935	0.065[a]	0.935
2	0.69	0.28[a]	0.69	0.69	0.69	0.69
3	0.065[a]	0.935	0.065[a]	0.635	0.185[a]	0.635
4	0.92	0.92	0.92	0.92	0.085[a]	0.92
5	0.33[a]	0.68	0.68	0.68	0.68	0.68
6	0.68	0.68	0.68	0.68	0.75	0.23[a]
7	0.26[a]	0.72	0.72	0.72	0.72	0.72
8	0.06[a]	0.86	0.06[a]	0.86	0.86	0.86
Results of evaluation and decision	0.38[a]	0.75	0.60	0.77	0.51[a]	0.71
	6	2	4	1	5	3

[a] The result is less than 0.6, representing the poor conceptual design scheme.

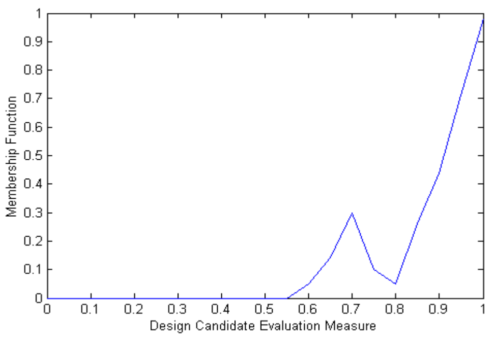

Fig. 12. Membership function of the output fuzzy set.

network are listed as below:

$$(0,0),(0.05,0),(0.10,0),(0.15,0),(0.20,0),(0.25,0),(0.30,0),$$
$$(0.35,0),(0.40,0),(0.45,0),(0.50,0),(0.55,0),(0.60,0.05),$$
$$(0.65,0.14),(0.70,0.30),(0.75,0.10),(0.80,0.05),(0.85,0.26),$$
$$(0.90,0.44),(0.95,0.71),(1.00,0.98).$$

The final evaluation and decision value was obtained by calculating the center of the output membership function. The final evaluation and decision value considering the fourth evaluation metric and the first customer requirement for the first conceptual design scheme was obtained as 0.89, as shown in Fig. 12.

In the same way, the evaluation and decision value considering other evaluation metrics and customer requirements for the first conceptual design scheme were obtained, as shown in Table 12. As mentioned above, when an evaluation metric and a customer requirement had no relationship, or had a very weak relationship (less than 1/12), it was considered impossible to achieve the evaluation and decision value. The corresponding place to describe the evaluation and decision value is indicated with a blank.

For each time, the average of evaluation and decision value, $S_j(j=1,2,\cdots,M)$, considering all customer requirements was then obtained using Eq. (6), and the evaluation and decision value considering all evaluation metrics and all customer requirements, S, was calculated as 0.38 by averaging all the S_j values using Eq. (7).

Generally, when an evaluation and decision value was greater than the threshold value, say 0.6, the conceptual design scheme was considered good, otherwise poor. Because the value for the first conceptual design scheme was 0.38<0.6, this scheme was considered a poor scheme. The threshold value is purely case-dependent and can be determined by experts.

The final evaluation and decision values of the six conceptual design schemes considering all evaluation metrics and all customer requirements are summarized in Table 13.

From Table 13, it is easy to show that the fourth conceptual design scheme was chosen as the best one due to its highest evaluation and decision value. Therefore, scheme 4 was selected for the further development.

The analysis of the evaluation and decision results was mentioned below:

(1) The evaluation and decision is primarily determined by the satisfaction degree of evaluation metrics to the specification. When an evaluation metric satisfies the specification, the value is generally high (greater than 0.6), otherwise low (less than 0.6). When most of the evaluation metrics satisfy the specification, the conceptual design scheme is considered good.

(2) The importance of customer requirements, and the relationship between evaluation metrics and customer requirements also influence the final evaluation and decision values. For instance, both evaluation metrics 5 and 6 are related to customer requirement 4 with the values of 0.2 and 0.4, respectively. When considering scheme 2, though both of these two evaluation metrics satisfy the specification, the evaluation and decision value considering evaluation metric 6 is better than the evaluation and decision value considering evaluation metric 5.

(3) The evaluation and decision values also provide guidelines for scheme modification and redesign. The values below 0.6 indicate poor conceptual design schemes that generally cannot satisfy the customer requirements. Therefore, these conceptual design schemes should be modified. When a number of evaluation metrics do not satisfy the specification, the one with the lowest evaluation and decision value should be changed first due to its strongest influence on the evaluation and decision value. Even for the evaluation metrics that satisfy specification, the evaluation metrics with the evaluation and decision values near to or less than 0.6 should also be adjusted to improve the overall evaluation and decision value of the conceptual design schemes of products.

5. Conclusions

Customer requirements play a very important role in the evaluation and decision process of conceptual design schemes of products. Therefore, corporations should comprehensively collect information on customer requirements. The design process of customer requirements includes obtaining customer requirements, the prediction of customer requirements, and the analysis of customer requirements. After the design process of customer requirements is conducted, the job of evaluation and decision of conceptual design schemes of products is developed based on customer requirements. In this work, a method for the evaluation and decision of conceptual design schemes of products based on customer requirements is presented. The final evaluation and decision result based on this method could reflect reality properly and make the evaluation and decision job reasonable and acceptable. In summary, the main contributions of this paper lie in three points: (1) An improved method is developed to compute the weights of customers requirements by using the AHP with a strategy of modifying the judgment matrix; (2) To convert the qualitative requirement from customers to a quantitative metric, the relation between the customer requirements and the evaluation metric has been built with accounting for the fuzzy uncertainty from experts' judgments; and (3) Fuzzy reasoning method together with BP neural network is put forth to evaluate the conceptual design scheme.

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