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A fuzzy-AHP approach to prioritization of CS attributes in target planning for automotive product development

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A R T I C L E I N F O

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A B S T R A C T

Understanding customer requirements and incorporating them into the conceptual vehicle design is the first step of automotive product development (PD). However, lack of quantitative data and undefined relationships between the attributes makes it difficult to develop a quantitative model for analyzing subjective customer satisfaction (CS) attributes. While researchers and practitioners have accomplished a significant success in terms of developing tool such as quality function deployment (QFD) to capture the voice of customers, and mathematical models for selecting engineering design alternatives, there is limited precedence in terms of prior works on customer satisfaction driven quality improvement target planning and prioritization of customer satisfaction attributes for target planning. This paper presents a fuzzy set theory based analytic hierarchy process (fuzzy-AHP) framework for prioritizing CS attributes in target planning. Furthermore, unlike prior QFD papers, we consider a broad range of strategic and tactical factors for determining the weights. These weights are then incorporated into target planning by identifying the gap in the current CS level. A case example from automotive industry is presented to demonstrate efficacy of the proposed methodology. The framework has been implemented on MS Excel® so that the industry can easily adopt it with limited amount of training and at no additional software cost.

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1. Introduction

The automotive industry is striving hard to continuously develop higher quality products and improve business effectiveness. The industry uses various customer satisfaction attributes to improve the design of a vehicle. J.D. Power and Associates index is perhaps the most popular customer satisfaction survey used in automotive world (Power & Associates, 2007). They consider 77 vehicle attributes to measure customer satisfaction (CS). Both industry and customers consider these vehicle attributes as critical vehicle performance indicators and therefore important purchasing decision factors. Therefore, the auto industry uses them as one of the quantifiable measures to assess the vehicle performance, to identify potential improvement areas in CS and set future targets for further improvement. Generally, the customer satisfaction targets for vehicle attributes are set at the corporate level based on business and market consideration.

Realistically, it is not feasible to address all the potential attributes at once due to such practical constraints as the availability of budget and time, corporate strategic planning, product differentiation strategy, competitive product features, to name a few. Moreover, not all auto companies give equal importance to each attribute because every individual company tries to compete on different product features and attributes. This necessitates the prioritization of potential improvement opportunities (or vehicle attributes) while taking into consideration the existing gap and other practical consideration as mentioned above. However, the challenge is that most of these practical considerations are imprecise (or fuzzy), lacking quantitative measures, and often conflicting in nature. The top management always deliberates these issues in target planning process; however, there is no structured methodology available in public domain that provides a mechanism to capture these considerations in attribute prioritization and CS target setting.

The determination of correct relative importance of CS (vehicle) attributes is extremely important in order to achieve total alignment of continuous improvement efforts with corporate (business) strategy. Kano model (Kano, Seraku, Takahashi, & Tsuji, 1984) has been widely used by the design community to identify and prioritize those few attributes that have more potential to achieve higher CS (CQM, 1993; Yadav & Goel, 2008). Although various methods have been proposed to assign weights to the identified customer requirements, not much has been reported on the prioritization

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of vehicle attributes. Ho, Lai, and Chang (1999) propose a group decision-making technique for obtaining the importance weights for the customer requirements. Analytic hierarchy process (AHP) developed by Saaty (1980) has been widely used in weighting customer requirements. Gustafsson and Gustafsson (1994) use a conjoint analysis method to determine the relative importance of the customer requirements. All these methods employ pair-wise comparisons of customer requirements to determine their relative importance.

Interestingly, the pair-wise comparison methods are based on crisp real number. However, in reality the expert's assessment in pair-wise comparison is always subjective and imprecise (Chan, Kao, Ng, & Wu, 1999). In order to deal with this deficiency, Kwong and Bai (2002, 2003) propose a fuzzy-AHP with an extent analysis approach to determine the importance weights for the customer requirements in quality function deployment (QFD). Another recent application of the integrated fuzzy-AHP model is proposed by Sun, Ma, Fan, and Wang (2008) in the selection of experts for evaluating R&D projects. However, the prioritization of CS vehicle attributes for target planning presents different and rather unique challenge of ensuring complete alignment of CS driven quality improvement efforts with corporate business strategy. The failure to do so will result in mismatch between corporate level business strategy and product development initiatives. Therefore, our intent in this research is to address the need for a comprehensive methodology for prioritization of CS attributes by dealing with subjective and imprecise assessments and ensuring proper alignment between corporate strategy and quality improvement initiatives in PD process.

The objective of this paper is to present a fuzzy-AHP framework for determining the relative importance of customer satisfaction attributes in target planning decisions to improve the functionality and performance of a product. With the AHP component, we determine the relative importance of product CS attributes more rationally by synthesizing all available information about the decision in a system-wide and systematic manner. The model further helps us to rank order the attributes by considering multiple factors according to the preference of decision makers. However, AHP's pair-wise comparison process involves semantic judgment and linguistic comparisons and uses ratings scale like "highly important than", "moderately important than" etc. which are "fuzzy" in nature. This is especially the case when the CS attributes are set at the corporate level. In order to analyze this subjective information, we propose a fuzzy logic based approach and perform sensitivity analysis of designer's confidence level on human judgment versus CS attributes prioritization decisions. Unlike Kwong and Bai (2002) application of fuzzy-AHP in QFD, our framework incorporates broader strategic factors (than just engineering) such as marketing, and long term strategic related criteria in target planning. Thereby, our framework integrates the corporate level business strategy with the product development initiatives. Another advantage of our approach is that the whole framework is implemented on MS Excel® which facilitates the adoption process in industry without incurring any additional cost for the software. While this paper discusses automotive case example to demonstrate the methodology, the proposed framework can be applied to any prioritization decision making setting involving multiple factors with limited information and dealing with semantic comparisons.

Section 2 describes the fuzzy-AHP methodology for prioritization of customer satisfaction attributes for target planning; Section 3 presents a case example from automotive application; in Section 4, we discuss results, sensitivity analysis and its utility in target planning; and finally Section 5 summarizes the contribution of the paper with some concluding remarks and a direction for future work.

2. Suitability of fuzzy-AHP for CS attributes prioritization problem in target planning

The traditional form of AHP has been widely used across the industry in many applications such as for project selection (Mustafa & Al-Bahar, 1991), setting priorities, allocating resources (Barbarosoglu & Pihas, 1995), measuring performances (Lee, Kwak, & Han, 1995), resolving conflict, and dealing with quality management, and strategic planning and policy making (Hongre, 2006). Cimren, Catay, and Budak (2007) have developed a decision support system for tool selection while Liu and Wu (2005) used AHP for supplier selection problem. Sharma and Gandhi (2006) have used it for determining remaining useful life of lube oil. The AHP treats the decision as a system and provides a structured approach to solving complex problems. In early stages of product development, the decision makers have limited or no clue about the relationship between different CS attributes or factors and how they can possibly be mapped with vehicle attributes. Decision makers struggle with many important but ill-defined attributes in terms of prioritizing and pursuing them for further actions to improve the functionality and performance of the product. Bounded rationality and limited cognitive processes make it nearly impossible for the decision maker to adequately consider all of the factors in a complex screening decision. Without a structured approach, the design engineers and PD managers are likely to base their decisions on only a subset of important criteria without understanding their relative importance and interactions. The AHP provides a framework for solving different types of complex and multi-criteria decision making problems based on the relative importance assigned to each criterion's contribution in accomplishing the stated goal or objective (Handfield, Walton, Sroufe, & Monczka, 2002). It employs a system-wide solution approach in systematic manner by synthesizing all available information that otherwise might not be possible (Handfield et al., 2002).

In this research, we use a fuzzy-AHP approach for determining the weights for CS attributes, because, early in the PD process the weight determination problem primarily depends on subjective judgment (or preference) of the design team. In such a situation, it is difficult to incorporate preference scales (such as "less likely", "more likely" etc.) in the analytical models. In fact, the meaning of "preference" is already embedded in fuzziness and human semantics. Therefore, using a crisp value for pairwise comparison is not suitable because it does not accurately represent the individual semantic cognition state of the decision makers. Fuzzy logic (Zadeh, 1965) is a proven scientific technique that allows us to convert linguistic measures into crisp measure using membership functions. Membership functions define the fuzzy boundary between two measurements scales such as 'less likely' and 'likely".

2.1. The proposed fuzzy-AHP model

Except for the fuzzy representation of pairwise comparison, the other steps in the proposed fuzzy-AHP model are same as those in the traditional AHP. The basis of AHP method is the hierarchical representation that helps to solve a complex problem through successive simple processes (Hongre, 2006). It requires a problem to be decomposed into levels, each of which is comprised of elements or factors. The elements of the hierarchy in a given level are mutually independent, but comparable to the elements of the same level. Each element must connect to at least one element of the next higher level, which is considered as a criterion according to which we compare the elements of the next level below. Typically, the following steps are required in an AHP model (Udo, 2000).

1. Structure a problem with a model that shows the problem's key elements and their relationship.
2. Compare elements in pairs by eliciting judgments that reflect knowledge, feelings, or emotions.
3. Represent those judgments with meaningful numbers.
4. Use these numbers to calculate the priorities of the elements of the hierarchy.

2.1.1. Pairwise comparison

Let $\mathbf{E} = (e_1, e_2, \ldots, e_n)$ be a set of homogeneous elements (factors or criteria) of a component (set of criteria at a given level) and a point of view. The method assists us in quantifying the relative dominance (importance) of the elements of **E** in terms of viewpoints. The comparison process requires that a number of weights be assigned to each pair of elements (e_i, e_j) with respect to a viewpoint. Table 1 shows the pairwise comparison scale developed by Saaty (1977) for the traditional AHP. It allows converting the subjective or qualitative judgments into numerical values. When making pairwise comparisons, the decision maker estimates how many times he or she prefers (in case of giving preferences) one element than the other according to a given criterion or attribute, or how many times more important he or she judges an element as compared to the other one according to a given criterion or attribute. The pairwise comparisons are applied to every elements of a component at a given level in the hierarchy according to elements of the next higher level.

For computing the priorities of elements, a judgmental matrix (also known as pairwise comparison matrix) is constructed as shown below.

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \ldots & a_{1n} \\ 1/a_{12} & 1 & a_{23} & \ldots & a_{2n} \\ \ldots & \ldots & 1 & \ldots & \ldots \\ 1/a_{n1} & \ldots & \ldots & \ldots & 1 \end{bmatrix} \quad (1)$$

where, a_{ij} represents a pairwise comparison if the element e_i dominates e_j (greater than or equal to one). On the other hand, $1/a_{ij}$ represents a similar comparison if the element e_i dominates e_j (less than or equal to one). Likewise, '1' means if none of the elements dominate other, and '0' means a judgment is not available. The entries a_{ij} are governed by the following rules:

$$a_{ij} > 0; a_{ij} = 1/a_{ji}; a_{ii} = 1 \quad \forall i. \quad (2)$$

In the fuzzy-AHP model, instead of being discrete, the numbers 1–9 represent triangular fuzzy numbers, which are used to capture the subjectivity or vagueness of the pairwise preferences of CS attributes. Fig. 1 shows the fuzzy set definition of five triangular fuzzy numbers with the corresponding membership function. The fuzzy set is defined as $F = \{(x, \mu(x)), x \in U\}$, where x takes it's values on the real line. U is the universe of discourse, $\mu(x)$ is membership function whose values lie between [0, 1].

Table 1
The traditional form of AHP pairwise comparison scale.

Numerical rating	Verbal scale	Description
1	Equal importance of both elements	Two elements contribute equally
3	Moderate importance of one element over another	Experience and judgment favor one element over another
5	Strong importance of one element over another	An element is strongly favored
7	Very strong importance of one element over another	An element is very strongly dominant
9	Extreme importance of one element over another	An element is favored by at least an order of magnitude
2,4,6,8	Intermediate values	Used to compromise between two judgments

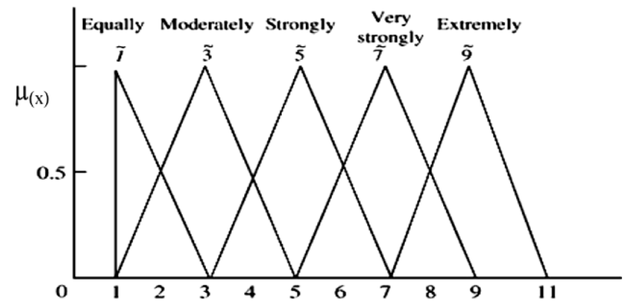

Fig. 1. Fuzzy set definition with triangular membership function.

Mathematically, the triangular type fuzzy membership function is defined as

$$\mu(x) = \begin{cases} 0 & x < l \\ \frac{x-1}{m-1} & l \le x \le m \\ \frac{u-x}{u-m} & m \le x \le u \\ 0 & x > u \end{cases} \quad (3)$$

Alternatively, in terms of interval of confidence α (or alpha-cut), the triangular fuzzy number can be represented as follows (Kwong & Bai, 2002):

Let $\widetilde{M} = (l, m, u)$ be the triangular fuzzy number where $l \leqslant m \leqslant u$, then

$$\widetilde{M}_\alpha = [l^\alpha, u^\alpha] = [(m-l)\alpha + l, -(u-m)\alpha + u)] \quad \forall \alpha \in [0, 1] \quad (4)$$

The common arithmetic operators for positive fuzzy numbers using the interval of confidence (or alpha-cut) are (Kauffman & Gupta, 1988):

$$\begin{aligned} &\forall m_L, m_R, n_L, n_R \in R^+, \quad \widetilde{M}_\alpha = [m_L^\alpha, m_R^\alpha], \quad \widetilde{N}_\alpha = [n_L^\alpha, n_R^\alpha], \ \alpha \in [0, 1] \\ &\widetilde{M} \oplus \widetilde{N} = [m_L^\alpha + n_L^\alpha, m_R^\alpha + n_R^\alpha] \\ &\widetilde{M} \Theta \widetilde{N} = [m_L^\alpha - n_R^\alpha, m_R^\alpha - n_L^\alpha] \\ &\widetilde{M} \otimes \widetilde{N} = [m_L^\alpha n_L^\alpha, m_R^\alpha n_R^\alpha] \\ &\widetilde{M} \varnothing \widetilde{N} = [m_L^\alpha / n_R^\alpha, m_R^\alpha / n_L^\alpha] \end{aligned} \quad (5)$$

Having defined the membership functions for the fuzzy set, the fuzzy judgment matrix is constructed to represent the designer's pairwise preference of CS attributes with respect to the one level high viewpoint as explained earlier. In its general form, the fuzzy judgment matrix takes the the following form.

$$\widetilde{A} = \begin{pmatrix} 1 & \tilde{a}_{12} & \tilde{a}_{13} & \ldots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \tilde{a}_{23} & \ldots & \tilde{a}_{2n} \\ \ldots & \ldots & 1 & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 1/\tilde{a}_{1n} & \ldots & \ldots & \ldots & 1 \end{pmatrix} \quad (6)$$

where, $a_{ij} = \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$, these number are similar to the pairwise comparison scales as defined by Saaty (1977) but are fuzzy in nature.

2.1.2. Determination of weights by computing fuzzy eigenvalues

In case of crisp pairwise comparison matrix, weights of the attributes can be estimated by finding the principal eigenvector w of the matrix A (Saaty, 2000).

$$\boldsymbol{Ax} = \lambda_{\max}\boldsymbol{x} \quad (7)$$

where, A is an $n \times n$ fuzzy matrix containing crisp numbers and $\boldsymbol{x}$ is non-zero $n \times 1$ crisp vector representing of crisp numbers x_i. When

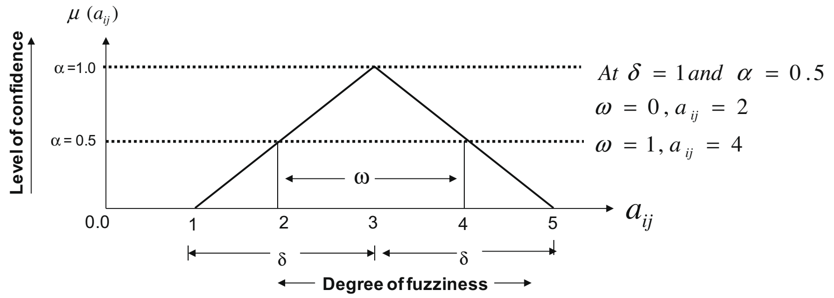

Fig. 2. Fuzzy parameters defined-alpha cut and index of optimism (adapted from Promentilla (2006)).

the vector $\boldsymbol{x}$ is normalized, it becomes the vector of priorities of elements of one level with respect to the upper level. $\lambda_{\max}$ is the largest eigenvalue of the matrix A. This process is repeated at every level of the hierarchy. The aim is to determine the relative preferences (weights) of all elements on the same level according to each element on the next higher level.

Since we are analyzing fuzzy matrices, Eq. (7) needs to be converted into its fuzzy equivalent as below (Kwong & Bai, 2002):

$$[a^{\alpha}_{i1l}x^{\alpha}_{1l}, a^{\alpha}_{i1u}x^{\alpha}_{1u}] \oplus \cdots \oplus [a^{\alpha}_{inl}x^{\alpha}_{nl}, a^{\alpha}_{inu}x^{\alpha}_{nu}] = [\lambda x^{\alpha}_{il}, \lambda x^{\alpha}_{iu}] \tag{8}$$

where,

$$\widetilde{A} = [\tilde{a}_{ij}], \quad \tilde{x} = (\tilde{x}_1, \ldots, \tilde{x}_n),$$
$$\tilde{a}^{\alpha}_{ij} = [a^{\alpha}_{ijl}, a^{\alpha}_{iju}], \quad \tilde{x}^{\alpha}_i = [x^{\alpha}_{il}, x^{\alpha}_{iu}] \text{ and } \tilde{\lambda}^{\alpha} = [\lambda^{\alpha}_l, \lambda^{\alpha}_u]$$

The subscripts 'l' and 'u' represent the lower and upper values of fuzzy set defined in the fuzzy membership function (see Fig. 2). The next step is to convert fuzzy preference or judgment matrix into crisp judgment matrix by using the following equation

$$\hat{a}^{\alpha}_{ij} = \omega a^{\alpha}_{iju} + (1-\omega) a^{\alpha}_{ijl}, \quad \forall \omega \in [0,1] \tag{9}$$

where ω, known as index of optimism, is a linear convex combination and indicates degree of optimism of decision maker towards the judgment (Promentilla, 2006). Fig. 2 shows triangular fuzzy set defined in term of level of confidence (α) and index of optimism, ω. Likewise, δ is known as degree of fuzziness. When $\delta = 0$ and $\alpha = 1$, there is no difference between fuzzy preference and crisp preference numbers.

However, for a given delta, any deviation of alpha from 1 (i.e., <1) represents the level of uncertainty or reduced level of confidence of a decision maker. The value of ω reflects the attitude of decision maker towards the fuzziness in the judgment. Accordingly, when ω approaches to 0, it reflects design engineer's attitude inclined towards more moderate values or underestimation of the crisp value. Alternatively, ω approaching to 1 reflects that the design engineer's attitude is inclined towards more extreme values or an overestimation of the crisp value. Therefore, using Eq. (9) and the concepts explained in Fig. 2, we can convert the fuzzy judgment matrix into its crisp form by substituting the values for α and ω. These values are fixed for a given decision making scenario (such as level of uncertainty or confidence on the judgment and the general attitude of the decision maker towards fuzziness).

3. Prioritization of CS attributes – an example from automotive product development

In the auto industry, vehicle characteristics (or requirements) are measured in terms of attributes such as fuel economy, emission, vehicle dynamics, performance, NVH (noise, vibration, and harshness), aerodynamics, climate control, packaging, cost, weight, etc. Each of these characteristics can serve as an objective for improvement of customer satisfaction target. These attributes are classified into 'must-be' attributes, performance or one-dimensional attributes, and attractive attributes. As suggested in Yadav and Goel (2008), one-dimensional attributes are potential candidates to achieve the improvement in customer satisfaction. However, within this category alone, there may be several attributes that cannot be pursued at once due to practical constraints such as availability of budget and time, corporate strategic planning, and product differentiation strategy. The current PD literature lacks a comprehensive approach that can help vehicle program managers with the prioritization of these attributes especially in dealing with subjective and incomplete information. The proposed fuzzy-AHP based methodology provides a framework for prioritization of CS attributes at early stages of PD process. The methodology can be divided into four steps as described in the following paragraphs.

Step 1: benchmarking and building of model hierarchical structure

In addition to selecting a list of potential CS attributes, this step includes identification of the criteria and the sub-criteria for prioritization. It is typically done through internal and external benchmarking of best practices. In this paper, we present an example of prioritization of one dimensional customer satisfaction attributes for automotive product development. Unlike the traditional QFD literature, the proposed approach selects CS attributes that are more aligned with the company's strategic goals to achieve the long term objectives as well as design objectives. The precedent QFD literature (e.g., Kwong and Bai, 2002) largely includes only design related objectives to compare customer requirements. Fig. 3 depicts the hierarchical structure of 13 CS attributes and other major criteria and sub-criteria used to prioritize CS attributes for target planning process in order to improve the functionality and performance of the product.

The major criteria (U_i) represent a combination of long term strategic and short term tactical factors. These include alignment with corporate business strategy, product improvement opportunities, and financial consideration. These criteria are further divided into eight sub-criteria, which are represented as U_{ij}'s in the hierarchical structure diagram (Fig. 3). At the next lower level, we consider 13 CS attributes that significantly influence the identified criteria and sub-criteria. The first group of CS attributes (A_k, $k = 1, 2, 3$) represent the attributes that are aligned with a company's strategic goals such as producing more fuel efficient cars, cross over type exterior styling, and a reasonably well powered engines. In other words, these may require significant change in design to support company's strategy to capture the niche market. The second group of attributes (A_k, $k = 4, 5, \ldots, 10$) includes the functionalities and performance improvement opportunities for the product. While these may also call for moderate to significant design changes, unlike the first group these may not provide the niche market. However, these attributes are very important to stay competitive in the marketplace. Lastly, the third group of CS

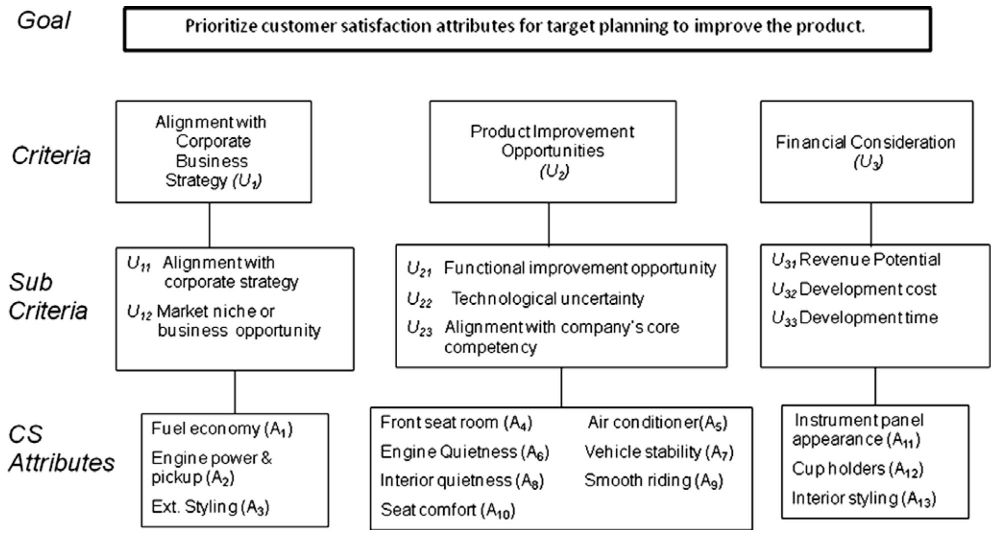

Fig. 3. Analytic hierarchy structure for prioritization of CS attributes in an automotive PD.

attributes (A_k, $k = 11, 12, 13$) provide the excitement to the customer. These attributes may not have any significant impact on the functional performance of the product but they provide the convenience to the user.

Step 2: construction of pairwise comparison matrices (PCM)

The pairwise comparison process requires inputs from multiple layers of decision makers such as functional managers, program managers and further upper level executives who make strategic decisions for the company. Therefore, in order to get a good and reliable data, the subject matter experts should be chosen carefully. For example, a high level management team should be chosen for comparing the relative importance of U_i ($i = 1, 2, 3$) major criteria because they are responsible for determining the future product and market strategy for the company. In the next level, for pairwise comparison of $U_{ij}(\forall i, j)$ with respect to each U_i, vehicle design and marketing experts should be asked to compare the elements for each level in accordance with their areas of expertise in terms of preference scale given in Table 1. Lastly, the pairwise comparison of CS attributes (A_k: $k = 1, 2, \ldots, 14$) in relation to U_{ij} should be done by corresponding functional departments. Fig. 4 represents the major criteria PCM for the given automotive PD example. Similarly, Figs. 5 and 6 illustrate the sub-criteria PCMs and a subset of CS attribute PCMs. The remaining CS attributes PCM's are given in Appendix A. Note that these matrices consist of triangular fuzzy numbers.

Fig. 4 shows that *strategic alignment* is 'moderately important' and 'very strongly important' over *product improvement opportunities* and financial considerations respectively. Likewise, *product improvement opportunities* is 'moderately important' over *financial consideration*.

	U_1	U_2	U_3
U_1	1	$\tilde{3}$	$\tilde{7}$
U_2	$1/\tilde{3}$	1	$\tilde{3}$
U_3	$1/\tilde{7}$	$1/\tilde{3}$	1

Fig. 4. Fuzzy pairwise comparison matrix for major criteria U_i ($i = 1, 2, 3$) in relation to overall prioritization goal.

Step 3: calculation of eigenvectors of elements by solving fuzzy PCM

The objective of this step is to compute the relative importance (or principal eigenvector) of all the elements with respect to their next higher level element in the hierarchy. We do so by first converting the fuzzy PCMs into their respective crisp PCMs and then computing the eigenvectors by following the typical AHP procedures.

3.3.1. Conversion of fuzzy PCM to crisp PCM

In this step, the first task is to define the lower limit and upper limit of the fuzzy numbers with respect to α-cut values by applying the Eq. (4). That is,

$$\tilde{1}^{\alpha} = [1, 3 - 2\alpha], \quad 1/\tilde{1}^{\alpha} = \left[\frac{1}{3 - 2\alpha}, 1\right]$$

Alignment with Corp. Business Strategy (U_1)

	U_{11}	U_{12}
U_{11}	1	$\tilde{5}$
U_{12}	$1/\tilde{5}$	1

Product Improvement Opportunities (U_2)

	U_{21}	U_{22}	U_{23}
U_{21}	1	$1/\tilde{5}$	$1/\tilde{3}$
U_{22}	$\tilde{5}$	1	$\tilde{1}$
U_{23}	$\tilde{3}$	$1/\tilde{1}$	1

Financial Consideration (U_3)

	U_{31}	U_{32}	U_{33}
U_{31}	1	$1/\tilde{5}$	$1/\tilde{3}$
U_{32}	$\tilde{5}$	1	$\tilde{1}$
U_{33}	$\tilde{3}$	$1/\tilde{1}$	1

Fig. 5. Fuzzy pairwise comparison matrices for sub-criteria U_{ij} in relation to major criteria.

Strategic Alignment (U_{11})

	A_1	A_2	A_3
A_1	1	$\tilde{1}$	$\tilde{7}$
A_2	$1/\tilde{1}$	1	$\tilde{5}$
A_3	$1/\tilde{7}$	$1/\tilde{5}$	1

Market Niche (U_{12})

	A_1	A_2	A_3
A_1	1	$\tilde{3}$	$\tilde{7}$
A_2	$1/\tilde{3}$	1	$\tilde{3}$
A_3	$1/\tilde{7}$	$1/\tilde{3}$	1

Fig. 6. Fuzzy pairwise comparison matrices of CS attributes in relation to *strategic alignment* and *market niche* sub-criteria.

$$\tilde{3}^{\alpha} = [1 + 2\alpha, 5 - 2\alpha], \quad \tilde{3}^{\alpha^{-1}} = \left[\frac{1}{5 - 2\alpha}, \frac{1}{1 + 2\alpha}\right]$$
$$\tilde{5}^{\alpha} = [3 + 2\alpha, 7 - 2\alpha], \quad \tilde{5}^{\alpha^{-1}} = \left[\frac{1}{7 - 2\alpha}, \frac{1}{3 + 2\alpha}\right]$$
$$\tilde{7}^{\alpha} = [5 + 2\alpha, 9 - 2\alpha], \quad \tilde{7}^{\alpha^{-1}} = \left[\frac{1}{9 - 2\alpha}, \frac{1}{5 + 2\alpha}\right]$$
$$\tilde{9}^{\alpha} = [7 + 2\alpha, 11 - 2\alpha], \quad \tilde{9}^{\alpha^{-1}} = \left[\frac{1}{11 - 2\alpha}, \frac{1}{7 + 2\alpha}\right]$$

Next, let's say, $\alpha = 0.5$; that is decision maker has an average confidence on the judgment made during the construction of PCM's. Upon substituting the value of α into above expressions, we can convert the triangular fuzzy numbers into an α-cut range. Subsequently, these ranges are used in place of the fuzzy numbers to convert fuzzy PCM's into α-cut fuzzy PCM's. Fig. 7 depicts the alpha-cut fuzzy comparison matrix for major criteria. Similarly, Figs. 8 and 9 illustrate the alpha-cut fuzzy PCM for sub-criteria and three attributes. The alpha-cut fuzzy comparison matrices for remaining attributes are given in Appendix B.

Lastly, these alpha-cuts fuzzy PCM's are converted into their crisp form by plugging in the value of ω into Eq. (9). Without any loss of generality, in this study we have used $\omega = 0.5$ as the value of index of optimism. This means that the judgments are neither too optimistic nor too pessimistic. The matrices shown in Figs. 10–12 represent the crisp pairwise comparison of elements at various levels. For example, Fig. 10 represents crisp PCM of the three main criteria with respect to the overall prioritization goal of CS attributes. Also shown in the table are the values for relative importance of major criteria w_{U_i}, highest eigenvalue ($\lambda_{\max}$), consistency index (CI), and consistency ratio (CR), which will be explained in the following sections.

3.3.2. Calculation of Eigenvectors to determine the relative importance of elements

The eigenvector or relative importance of elements can be computed in multiple ways (Saaty, 1980). First method is by solving the characteristic equation of matrix **A**, $\det(\mathbf{A} - \lambda\ \mathbf{I}) = \mathbf{0}$, and then substituting the largest eigenvalue into the equation, $\mathbf{AX} = \lambda_{\max}\mathbf{X}$. Finally upon normalization of X_i-values will get the relative importance of the element *i*. A relatively simple approach to determine the prioritization weight (relative importance) is by using the following formula:

$$\boldsymbol{w_i} = \frac{\sum_{i=1}^{I}\left(\frac{aij}{\sum_{j=1}^{J} aij}\right)}{J} \tag{11}$$

where, $\boldsymbol{w_i}$ is the relative importance for criterion *i*. *J* is the index number of columns in the pairwise matrix, I is the Index number of rows in the pairwise matrix, a_{ij} is the Value of pair wise comparison between elements *i* and *j*.

This study uses the second approach (Eq. (11)) to calculate the relative importance of all the elements, that is, criteria, sub-criteria, and the CS attributes. The main motivation to use this approach was to being able to implement the whole framework on MS Excel®, which is widely used across the automotive industry.

	U_1	U_2	U_3
U_1	1	[2, 4]	[6, 8]
U_2	[1/4, 1/2]	1	[2, 4]
U_3	[1/8, 1/6]	[1/4, 1/2]	1

Fig. 7. α-Cuts fuzzy comparison matrix of major criteria (U_i) ($\alpha = 0.5$).

Alignment with corporate business strategy (U_1)

	U_{11}	U_{12}
U_{11}	1	[4, 6]
U_{12}	[1/6,1/4]	1

Product Improvement Opportunity (U_2)

	U_{21}	U_{22}	U_{23}
U_{21}	1	[1/6, 1/4]	[1/4, 1/2]
U_{22}	[4,6]	1	[1,2]
U_{23}	[1/4,1/2]	[1/2,1]	1

Financial Consideration (U_3)

	U_{31}	U_{32}	U_{33}
U_{31}	1	[1/6, 1/4]	[1/4,1/2]
U_{32}	[4, 6]	1	[1, 2]
U_{33}	[2, 4]	[1/2, 1]	1

Fig. 8. α-Cuts fuzzy comparison matrix for the prioritization of sub-criteria ($\alpha = 0.5$).

Alignment with corporate business strategy(U_{11})

	A_1	A_2	A_3
A_1	*1*	*[1, 2]*	*[6, 8]*
A_2	*[1/2, 1]*	*1*	*[4, 6]*
A_3	*[1/8, 1/6]*	*[1/6, ¼]*	*1*

Market Niche (U_{12})

	A_1	A_2	A_3
A_1	1	[2, 4]	[6, 8]
A_2	[1/4, 1/2]	1	[2,4]
A_3	[1/8, 1/6]	[1/4, ½]	1

Fig. 9. α-Cuts fuzzy comparison matrix of CS attributes in relation to *strategic alignment* and *market niche* sub-criteria ($\alpha = 0.5$).

Prioritization Main Criteria	U_1	U_2	U_3	w_{Ui}		
U_1	1.000	3.000	7.000	0.660	**λ_{max}**	**3.090**
U_2	0.375	1.000	3.000	0.249	**C.I.**	**0.045**
U_3	0.146	0.375	1.000	0.091	**C. R.**	**0.087**

Fig. 10. Crisp PCM and relative importance of major criteria for prioritization of CS attributes.

Strategic Alignment (U_1)	U_{11}	U_{12}	w_{U1j}
U_{11}	1	5	0.830
U_{12}	0.208	1	0.170

Improvement Opportunity (U_2)	U_{21}	U_{22}	U_{23}	w_{U2j}		
U_{21}	1.000	0.208	0.375	0.116	**λ_{max}**	**3.100**
U_{22}	5.000	1.000	1.500	0.529	**C.I.**	**0.050**
U_{23}	3.000	0.750	1.000	0.355	**C. R.**	**0.096**

Financial Consideration (U_3)	U_{31}	U_{32}	U_{33}	w_{U3j}		
U_{31}	1.000	0.208	0.375	0.116	**λ_{max}**	**3.10**
U_{32}	5.000	1.000	1.500	0.529	**C.I.**	**0.05**
U_{33}	3.000	0.750	1.000	0.355	**C. R.**	**0.096**

Fig. 11. The relative importance of sub-criteria in relation to major criteria.

Corporate Strategic Alignment (U_{11})	A_1	A_2	A_3	w_{Ak}		
A_1	1.000	1.500	7.000	0.540	**λ_{max}**	**3.061**
A_2	0.750	1.000	5.000	0.383	**C.I.**	**0.031**
A_3	0.146	0.208	1.000	0.077	**C. R.**	**0.059**

Market Niche (U_{12})	A_1	A_2	A_3	w_{Ak}		
A_1	1.000	3.000	7.000	0.660	**λ_{max}**	**3.090**
A_2	0.375	1.000	3.000	0.249	**C.I.**	**0.05**
A_3	0.146	0.375	1.000	0.091	**C. R.**	**0.09**

Fig. 12. Relative importance of CS attributes $A_{k(k=1,\ 2,\ 3)}$ in relation to *strategic alignment* and *market niche* sub-criteria (U_{1j}, $j = 1, 2, 3$).

3.3.3. Checking for consistency of pairwise comparisons

One of the key advantages of AHP over other multi-objective decision models is being able to check the consistency in the judgments of decision makers. In order to check the consistency of our pairwise comparisons, we calculate λ_{max} and CI for all the PCMs as follows.

λ_{max} is determined by solving the equation

$$\mathbf{A}\boldsymbol{w} = \lambda_{max}\boldsymbol{w} \tag{12}$$

where, **A** is the crisp pairwise matrix and ***w*** is a column matrix of principal eigenvectors (relative importance of elements). Similarly, CI and CR were determined using the following formulas:

$$\left.\begin{aligned} \mathrm{CI} &= \tfrac{\lambda\max - n}{n-1} \\ \mathrm{CR} &= \tfrac{\mathrm{CI}}{\mathrm{RI}} \end{aligned}\right\} \tag{13}$$

Depending upon the size of the matrix, n, an appropriate value of random consistency index (RI) was chosen to calculate CR. See Table 2 for RI values. Saaty (1980) suggests that CR should be less than 0.1 in order for pairwise comparisons to be consistent and acceptable. In this study, the CR values for all of the twelve pairwise comparison matrices have been found to be less than 0.1. Fig. 11 shows the crisp pairwise matrices and relative importance of sub-criteria (U_{ij}) in relation to the major prioritization criteria (U_i). It also shows the largest eigenvalue, CI and CR (<0.1) validating the pairwise comparison. Similar process was applied to compute the relative importance of CS attributes (w_{Ak}) and were checked for the consistency ratio. Fig. 12 presents the results of prioritization weights calculations for first three CS attributes (A_k, $k = 1, 2, 3$) with respect to *strategic alignment* and *market niche* sub-criteria. The relative importance values of the remaining ten attributes are given in Appendix C.

Step 4: calculation of overall prioritization weights for each CS attributes

The overall or total prioritization weight (*TW*) of a CS attribute was calculated by considering the individual weights of all the relevant sub-criteria. Mathematically, it can be represented as follows:

$$TW_{Ak} = \sum_{k} \underset{i \in U_{ij}}{W_{U_i}} * \underset{U_{ij} \in A_{k*}}{W_{U_{ij}}} W_{A_k} \quad \forall k \tag{14}$$

Table 2
Average consistencies indexes of random matrices (Saaty, 1980).

Size	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

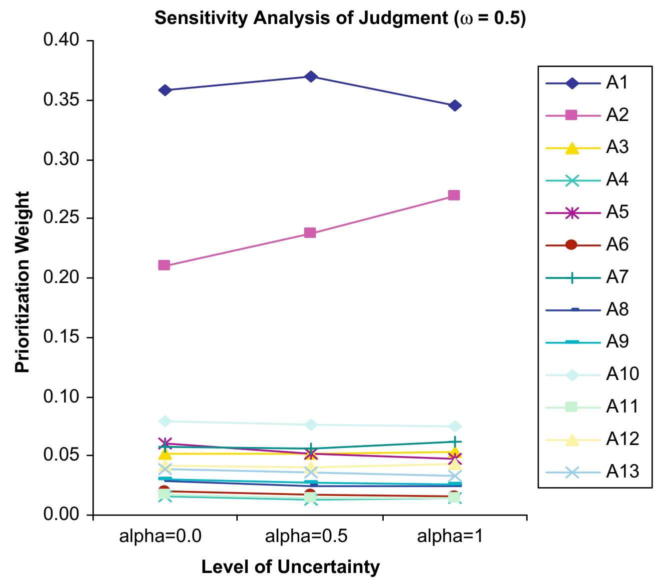

Fig. 13. Sensitivity analysis of uncertainty (confidence level) on attribute weights.

Table 3
Spreadsheet model showing the final results of prioritization weights for CS attributes.

Goal	Major criterion	Criterion rel. imp W_{U_i}	Sub criterion	SC rel. imp. $W_{U_{ij}}$	Cs attribute	Attr. rel. imp. W_{Ak}	Overall attribute weight TW_{Ak}
Determine the weights to prioritize the CS attributes			U_{11}	0.830	A_1	0.540	0.370
					A_2	0.383	0.238
					A_3	0.077	0.052
	U_1	0.660	U_{12}	0.170	A_1	0.660	
					A_2	0.249	
					A_3	0.091	
			U_{21}	0.116	A_4	0.069	0.014
					A_5	0.250	0.053
					A_6	0.103	0.018
					A_7	0.394	0.056
					A_8	0.064	0.022
					A_9	0.091	0.027
					A_{10}	0.029	0.076
	U_2	0.249	U_{22}	0.529	A_4	0.047	
					A_5	0.274	
					A_6	0.059	
					A_7	0.039	
					A_8	0.090	
					A_9	0.135	
					A_{10}	0.356	
			U_{23}	0.355	A_4	0.061	
					A_5	0.109	
					A_6	0.079	
					A_7	0.449	
					A_8	0.098	
					A_9	0.079	
					A_{10}	0.323	
			U_{31}	0.116	A_{11}	0.662	0.014
					A_{12}	0.274	0.040
					A_{13}	0.064	0.036
	U_3	0.091	U_{32}	0.529	A_{11}	0.091	
					A_{12}	0.249	
					A_{13}	0.660	
			U_{33}	0.348	A_{11}	0.097	
					A_{12}	0.790	
					A_{13}	0.113	
Sum		1.000					1.0

Where, $W_{\substack{U_i \\ i \in U_{ij}}}$ is the relative importance of major criterion U_i that is relevant to the sub-criteria U_{ij}. $W_{\substack{U_i j \\ U_{ij} \in A_k}}$ is the Relative importance of sub-criteria U_{ij} that are relevant to the CS attributes A_k. W_{A_k} is the Relative importance of an attribute A_k w.r.t to its next higher level sub-criterion and criterion. A_K is the Customer satisfaction attributes, $k = 1, 2, \ldots, 13$.

The final results of overall prioritization weight for each CS attribute are presented below in Table 3:

4. Results and discussion

The Fuzzy-AHP analysis suggests that attribute A_1 (fuel economy with weight 0.37) should be given the highest priority for target planning which is in line with the company's corporate business strategy. Among the thirteen attributes selected in this study, the second most important CS attribute is the engine power and pickup with a weight of 0.24 followed by interior quietness (0.08) and vehicle stability (0.06). Even though it is a stylized case example, the results obtained from this analysis provide an in-depth insight of the real problem being faced by the auto industry. With the oil price crisis in 2008, the fuel economy has become the main concern of the customer and the selling point for the manufacturer. However, as engine power is largely related to the engine size (i.e., in turn with fuel consumption), and the customers may not like to trade off the pickup power. Therefore, in order to stay competitive in the market, a fuel economical car with reasonably good powered engine should get the top priority amongst all the attributes. Similarly, attributes like interior noise and vehicle stability are likely factors in the purchasing decision of a car. It is logical because generally a light weight configuration is more fuel efficient but less stable and probably noisier too. These are the some of the key opportunities for design engineers to improve the vehicle's functional performance.

In addition, few other results on relative importance of CS attributes (Table 3) may be of equally significant interest to design community. For example, of the three main prioritization criteria, alignment with corporate business strategy is heavily weighted with 0.66 indicating that corporate level strategic decision is paramount to the success of the vehicle in the current marketplace. In relation to strategic alignment with corporate strategy sub-criteria, the decision maker has placed maximum weight on 'fuel economy' realizing that it is the only strategy going forward if the company wants to stay in the business. The distribution of weights assigned to various criteria, sub-criteria, and attributes provide hands-on

Product functional improvement opportunity (U_{21})

	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
A_4	1	$1/\tilde{5}$	$1/\tilde{3}$	$1/\tilde{7}$	$\tilde{1}$	$1/\tilde{1}$	$\tilde{5}$
A_5	$\tilde{5}$	1	$\tilde{1}$	$1/\tilde{1}$	$\tilde{5}$	$\tilde{5}$	$\tilde{7}$
A_6	$\tilde{3}$	$1/\tilde{1}$	1	$1/\tilde{7}$	$1/\tilde{1}$	$\tilde{1}$	$\tilde{3}$
A_7	$\tilde{7}$	$\tilde{1}$	$\tilde{7}$	1	$\tilde{7}$	$\tilde{7}$	$\tilde{7}$
A_8	$1/\tilde{1}$	$1/\tilde{5}$	$\tilde{1}$	$1/\tilde{7}$	1	$1/\tilde{3}$	$\tilde{3}$
A_9	$\tilde{1}$	$1/\tilde{5}$	$1/\tilde{1}$	$1/\tilde{7}$	$\tilde{3}$	1	$\tilde{5}$
A_{10}	$1/\tilde{5}$	$1/\tilde{7}$	$1/\tilde{3}$	$1/\tilde{7}$	$1/\tilde{3}$	$1/\tilde{5}$	1

Technological uncertainty (U_{22})

	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
A_4	1	$1/\tilde{5}$	$1/\tilde{3}$	$\tilde{1}$	$1/\tilde{3}$	$1/\tilde{5}$	$1/\tilde{5}$
A_5	$\tilde{5}$	1	$\tilde{5}$	$\tilde{5}$	$\tilde{5}$	$\tilde{5}$	$1/\tilde{3}$
A_6	$\tilde{3}$	$1/\tilde{5}$	1	$\tilde{1}$	$1/\tilde{3}$	$1/\tilde{1}$	$1/\tilde{5}$
A_7	$1/\tilde{1}$	$1/\tilde{5}$	$1/\tilde{1}$	1	$1/\tilde{3}$	$1/\tilde{5}$	$1/\tilde{7}$
A_8	$\tilde{3}$	$1/\tilde{5}$	$\tilde{3}$	$\tilde{3}$	1	$1/\tilde{3}$	$1/\tilde{3}$
A_9	$\tilde{5}$	$1/\tilde{5}$	$\tilde{1}$	$\tilde{5}$	$\tilde{3}$	1	$1/\tilde{5}$
A_{10}	$\tilde{5}$	$\tilde{3}$	$\tilde{5}$	$\tilde{7}$	$\tilde{3}$	$\tilde{5}$	1

Core competency of the company (U_{23})

	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
A_4	1	$1/\tilde{1}$	$1/\tilde{1}$	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{1}$	$1/\tilde{5}$
A_5	$\tilde{1}$	1	$\tilde{1}$	$1/\tilde{5}$	$\tilde{1}$	$\tilde{1}$	$1/\tilde{5}$
A_6	$\tilde{1}$	$1/\tilde{1}$	1	$1/\tilde{7}$	$1/\tilde{1}$	$\tilde{1}$	$1/\tilde{5}$
A_7	$\tilde{5}$	$\tilde{5}$	$\tilde{7}$	1	$\tilde{7}$	$\tilde{7}$	$1/\tilde{1}$
A_8	$\tilde{3}$	$1/\tilde{1}$	$\tilde{1}$	$1/\tilde{7}$	1	$1/\tilde{1}$	$1/\tilde{3}$
A_9	$\tilde{1}$	$1/\tilde{1}$	$1/\tilde{1}$	$1/\tilde{7}$	$\tilde{1}$	1	$1/\tilde{5}$
A_{10}	$\tilde{5}$	$\tilde{3}$	$\tilde{5}$	$\tilde{1}$	$\tilde{3}$	$\tilde{5}$	1

Fig. A.1. Fuzzy pairwise comparison matrix for CS attributes in relation to product improvement opportunities related sub-criteria.

Revenue Potential (U_{31})

	A_{11}	A_{12}	A_{13}
A_{11}	1	$\tilde{3}$	$\tilde{9}$
A_{12}	$1/\tilde{3}$	1	$\tilde{5}$
A_{13}	$1/\tilde{9}$	$1/\tilde{5}$	1

Development Cost (U_{32})

	A_{11}	A_{12}	A_{13}
A_{11}	1	$1/\tilde{3}$	$1/\tilde{7}$
A_{12}	$\tilde{3}$	1	$1/\tilde{3}$
A_{13}	$\tilde{7}$	$\tilde{3}$	1

Development Time (U_{33})

	A_{11}	A_{12}	A_{13}
A_{11}	1	$1/\tilde{7}$	$1/\tilde{1}$
A_{12}	$\tilde{7}$	1	$\tilde{9}$
A_{13}	$\tilde{1}$	$1/\tilde{9}$	1

Fig. A.2. Fuzzy pairwise comparison matrix for CS attributes in relation to financial consideration related sub-criteria.

information to formulate an order winning strategy for design engineers and marketing personnel.

4.1. Sensitivity analysis of level of uncertainty in pairwise comparison on prioritization decision

The determination of weights depends on the values of α and ω. In order to investigate this relationship, we ran few sensitivity analyses by varying the decision maker's level of confidence on judgments, that is from $\alpha = 0$ (most uncertain situation) to $\alpha = 1$ (most certain situation) under various situations such as from $\omega = 0$ (most pessimistic or underestimated situation) to $\omega = 0.95$ (highly optimistic or overestimated situation). Fig. 13 shows a sensitivity analysis graph of attribute weights when $\omega = 0.5$.

It shows that in all situations regardless of uncertainty level, fuel economy and engine performance are on the top of the priority list. However, the specific values of weights are changing depending upon the judgment situations. Although not shown here, in other analyses for the situations where we had $\omega = 0$ and 0.95, the values of weights varied modestly keeping the general trend unchanged. We believe that this kind of analysis provides design engineers with the right tools to weigh in on the various options and make an informed decision based on a scientific approach.

4.2. Using attribute weights in target planning to improve the product

In a typical PD process, in order to drive the development efforts, it is essential to set targets for any given product attribute. These targets need to be established to respond directly to customer requirements, corporate vision, and market strategies. The process of selecting potential attributes for further improvement and setting CS targets is known as target planning, which starts at top level of management. The output of the proposed methodology, the prioritized list of CS attributes or relative importance weights, can be a critical input to target planning process and provide a logical way to select potential attributes for further improvement.

Product functional improvement opportunity (U_{21})

	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
A_4	1	[1/6, 1/4]	[1/4, ½]	[1/8, 1/6]	[1, 2]	[1/2, 1]	[4, 6]
A_5	[4, 6]	1	[1, 2]	[1/2, 1]	[4,6]	[4,6]	[6, 8]
A_6	[2, 4]	[1/2, 1]	1	[1/8, 1/6]	[1/2, 1]	[1, 2]	[2, 4]
A_7	[6, 8]	[1, 2]	[6,8]	1	[6,8]	[6,8]	[6, 8]
A_8	[1/2, 1]	[1/6, ¼]	[1, 2]	[1/8, 1/6]	1	[1/4, ½]	[2, 4]
A_9	[1, 2]	[1/6, ¼]	[1/2, 1]	[1/8, 1/6]	[2, 4]	1	[4,6]
A_{10}	[1/6, ¼]	[1/8, 1/6]	[1/4, 1/2]	[1/8, 1/6]	[1/4, ½]	[1/6, ¼]	1

Technological uncertainty (U_{22})

	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
A_4	1	[1/6, ¼]	[1/2, 1]	[1, 2]	[1/4, ½]	[1/6, ¼]	[1/6, ¼]
A_5	[4,6]	1	[4,6]	[4,6]	[4,6]	[4,6]	[1/4, ½]
A_6	[1, 2]	[1/6, ¼]	1	[1,2]	[1/4, ½]	[1/2, 1]	[1/6, ¼]
A_7	[1/2, 1]	[1/6, ¼]	[1/2, 1]	1	[1/4, ½]	[1/6, ¼]	[1/8, 1/6]
A_8	[2, 4]	[1/6, ¼]	[2, 4]	[2, 4]	1	[1/4, ½]	[1/4, ½]
A_9	[4,6]	[1/6, ¼]	[1, 2]	[4, 6]	[2, 4]	1	[1/6, ¼]
A_{10}	[4,6]	[2, 4]	[4,6]	[6, 8]	[2, 4]	[4,6]	1

Alignment with company's core competency (U_{23})

	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
A_4	1	[1/2, 1]	[1/2, 1]	[1/6, 1/4]	[1/4, ½]	[1/2, 1]	[1/6, ¼]
A_5	[1, 2]	1	[1, 2]	[1/6, ¼]	[1, 2]	[1, 2]	[1/4, 1/2]
A_6	[1, 2]	[1/2, 1]	1	[1/8, 1/6]	[1/2, 1]	[1, 2]	[1/6, ¼]
A_7	[4, 6]	[4, 6]	[6,8]	1	[6,8]	[6,8]	[1/2, 1]
A_8	[2, 4]	[1/2, 1]	[1, 2]	[1/8, 1/6]	1	[1/2, 1]	[1/4, ½]
A_9	[1, 2]	[1/2, 1]	[1/2, 1]	[1/8, 1/6]	[1, 2]	1	[1/6, ¼]
A_{10}	[4, 6]	[2, 4]	[4, 6]	[1, 2]	[2, 4]	[4, 6]	1

Fig. B.1. α-Cuts fuzzy pairwise comparison matrix of CS attributes with respect to product improvement opportunities related sub-criteria, U_{2j} ($\alpha = 0.5$).

Revenue Potential

	A_{11}	A_{12}	A_{13}
A_{11}	1	[2, 4]	[8, 10]
A_{12}	[1/4, 1/2]	1	[4, 6]
A_{13}	[1/10, 1/8]	[1/6, 1/4]	1

Development Cost

	A_{11}	A_{12}	A_{13}
A_{11}	1	[1/4, 1/2]	[1/8, 1/6]
A_{12}	[2, 4]	1	[1/4, 1/2]
A_{13}	[6, 8]	[2, 4]	1

Development Time

	A_{11}	A_{12}	A_{13}
A_{11}	1	[1/8, 1/6]	[1/2, 1]
A_{12}	[6, 8]	1	[8, 10]
A_{13}	[1, 2]	[1/10, 1/8]	1

Fig. B.2. α-Cuts fuzzy pairwise comparison matrix of CS attributes in relation to financial consideration related sub-criteria, U_{3j} ($\alpha = 0.5$).

In some cases, the company might think of considering existing gap between their product and best in class product (or vehicle) while carrying out target planning process. The existing gap can be calculated by,

$$\Delta CS_i = CS_{i(BC)} - CS_{i(CV)} \quad (15)$$

where ΔCS_i represents the difference in customer satisfaction level between two vehicles for attribute i; $CS_{i(BC)}$ is customer satisfaction number of the best in class vehicle for a given attribute; and $CS_{i(CV)}$ is customer satisfaction number of company's current vehicle. The final prioritization ranking can be modified by incorporating existing CS gap between company's current vehicle and best in class vehicle and given as

$$PI_i = TW_{Ak} \times \Delta CS_i \quad (16)$$

where TW_{Ak} represents relative importance weight for A_k attribute obtained from AHP model. Any of these two indicators, relative importance weight (TW_{Ak}) or final prioritization ranking (PI_i), can be used to select potential attributes for further improvements and CS target setting. Yadav and Goel (2008) provide detailed discussion on CS target setting for each selected attributes.

5. Conclusions and future work

This paper has presented a fuzzy-AHP framework to determine the prioritization weights of CS attributes to facilitate the target planning decision in order to improve vehicle design. In contrast to the traditional AHP approach, the advantage of fuzzy based AHP allows the design community to have freedom of estimation as the judgment can vary from most optimistic to most pessimistic at various level of uncertainty. Further, the fuzzy theory provides a scientific approach to deal with semantic values of information that is generated during the pairwise comparisons. The entire framework has been implemented on MS Excel® to facilitate the adoption process in industry without incurring any additional cost for the software. Further, unlike the prior QFD literature, we consider a broader and strategic approach of prioritization problem and extend it to the target planning. The paper has also showed that the gap in customer satisfaction level can be incorporated to further refine the prioritization ranking of CS attributes provided company wants to given some consideration to current CS level.

The results obtained from this analysis provide an in-depth insight of the real problem facing the auto industry. A sensitivity analysis is performed to investigate the impact of confidence level of decision maker's on subjective judgment on the prioritization of CS attributes. The results from the automotive case study show that instead of focusing on small improvements on product functionality, the company needs to make a strong strategic decision to produce more fuel economical cars with a reasonable engine power to compete in the niche market. In overall, the proposed

Table C.1
Relative importance of CS attributes $A_{k(k=4,5,\ldots,10)}$ in relation to alignment with corporate business strategic alliance criterion and its sub-criteria (U_{2j}, j = 1,2,3).

Functional improvement	A_4	A_5	A_6	A_7	A_8	A_9	A10	w_{Ak}		
A_4	1	0.208	0.375	0.146	1.5	0.750	5	0.069	λ_{max}	7.897
A_5	5	1	1.5	0.750	5	5	7	0.250	CI	0.150
A_6	3	0.750	1	0.146	0.750	1.5	3	0.103	CR	0.111
A_7	7	1.5	7	1	7	7	7.000	0.394		
A_8	0.750	0.208	1.5	0.146	1	0.375	3	0.064		
A_9	1.5	0.208	0.750	0.146	3	1	5	0.091		
A_{10}	0.208	0.146	0.375	0.146	0.375	0.208	1	0.029		
Technological uncertainty										
A_4	1	0.208	0.750	1.5	0.375	0.208	0.208	0.047	λ_{max}	7.667
A_5	5	1	5	5	5	5	0.375	0.274	CI	0.111
A_6	1.5	0.208	1	1.5	0.375	0.750	0.208	0.059	CR	0.082
A_7	0.750	0.208	0.750	1	0.375	0.208	0.146	0.039		
A_8	3	0.208	1	3	1	0.375	0.375	0.090		
A_9	5	0.208	1.000	5	3	1	0.208	0.135		
A_{10}	5	3	5	7	3	5	1	0.356		
Core competency										
A_4	1	0.750	0.750	0.208	0.375	0.750	0.208	0.061	λ_{max}	7.554
A_5	1.5	1	1.5	0.208	1.5	1.5	0.375	0.109	CI	0.092
A_6	1.5	0.750	1	0.146	0.750	1.5	0.208	0.079	CR	0.068
A_7	5	5	7	1	7	7	0.750	0.449		
A_8	3	0.750	1.5	0.146	1	0.750	0.375	0.098		
A_9	1.5	0.750	0.750	0.146	1.5	1	0.208	0.079		
A10	5	3	5	1.5	3	5	1	0.323		

Table C.2
Relative importance of CS attributes $A_{k(k=11,12,13)}$ in relation to three sub-criteria under financial consideration criterion (U_{3j}, j = 1,2,3).

	A_{11}	A_{12}	A_{13}	w_{Ak}		
Revenue potential (U_{31})						
A_{11}	1.000	3.000	9.000	0.662	λ_{max}	3.080
A_{12}	0.375	1.000	5.000	0.274	CI	0.04
A_{13}	0.113	0.208	1.000	0.064	CR	0.08
Development cost (U_{32})						
A_{11}	1.000	0.375	0.146	0.091	λ_{max}	3.090
A_{12}	3.000	1.000	0.375	0.249	CI	0.05
A_{13}	7.000	3.000	1.000	0.660	CR	0.09
Development time (U_{33})						
A_{11}	1.000	0.146	0.750	0.097	λ_{max}	3.094
A_{12}	7.000	1.000	9.000	0.790	CI	0.05
A_{13}	1.500	0.113	1.000	0.113	CR	0.09

framework provides design engineers with a hands-on analytical tool to formulate an order wining strategy while considering any undertaking for product improvement. Furthermore, the proposed framework provides a structured decision making process, which can be repeated in any other similar problem setting beyond automotive involving multiple criteria and semantic judgments.

While there are many advantages of fuzzy-AHP methodology presented in the paper such as analytical basis for decision making and usability of tools when there is subjective or incomplete data, it may not be suitable for every problem due to time and complexity of the data collection process. The challenge may arise in terms of getting a consensus value for weights especially if we involve more than one expert in the judgment process. It is highly recommended that the experts have an agreement on the relative importance of each criterion with respect to its contribution to higher level objective. Following three scenarios are plausible in group decision making process.

– All the experts will have concurrence on their judgment. In this case, there is no dispute and we can use the consensus score for each pairwise comparison.
– Experts may differ on their judgment. In such case, one should try to achieve the agreement on the relative importance of the elements by using the technique such as Delphi method (Handfield et al., 2002). The experts are provided with the judgments of other group members and asked for re-evaluation. As a result, there is a possibility that the experts will agree on the consensus value.
– Experts may differ and Delphi or any other techniques to achieve consensus on the relative importance of elements fail. Although rarely but such situations do occur in the real world. In such cases, the weights for each element are separately based on each individual's judgment. At the end, an average weight for each element is calculated by combining the individual weights assigned by different experts for the element under question.

Further, the current approach does not incorporate the interaction between the prioritization criteria. For example, the fuel economy may be considered under multiple sub-criteria such as the "alignment with corporate business strategy" and the "product improvement opportunity". Such issues should be incorporated into the future decision analysis model for determining weights of CS attributes in target planning.

Appendix A

Figs. A.1 and A.2.

Appendix B

Figs. B.1 and B.2.

Appendix C

Tables C.1 and C.2.

References

Barbarosoglu, G., & Pihas, D. (1995). Capital rating in the public sector using the analytic hierarchy process. *The Engineering Economist, 40*(4), 315–329.
Chan, L. K., Kao, H. P., Ng, A., & Wu, M. L. (1999). Rating the importance of customer needs in quality function deployment by fuzzy and entropy methods. *International Journal of Production Research, 37*(11), 2499–2518.
Cimren, E., Catay, B., & Budak, E. (2007). Development of a machine tool selection system using AHP. *Journal of Advanced Manufacturing Technology, 35*, 363–376.
CQM (1993). A special issue on Kano's methods for understanding customer-defined quality. *Center for Quality of Management Journal, 2*(4), 3–35.
Gustafsson, A., & Gustafsson, N. (1994). Exceeding customer expectations. In *Proceedings of the sixth symposium on quality function deployment, Novi, MI* (pp. 52–57).
Handfield, R., Walton, S. V., Sroufe, R., & Monczka, R. (2002). Applying environmental criteria to supplier assessment: A study in the application of the analytic hierarchy process. *European Journal of Operational Research, 141*, 70–87.
Ho, E., Lai, Y., & Chang, S. I. (1999). An integrated group decision-making approach to quality function deployment. *IIE Transactions, 31*, 553–567.
Hongre, L. (2006). Identifying the most promising business model by using the analytic hierarchy process approach. In *Proceedings of the 23rd world gas conference, Amsterdam, Netherlands.*
Kano, N., Seraku, N., Takahashi, F., & Tsuji, S. (1984). Attractive quality and must-be quality. *Hinshitsu (The Journal of the Japanese Society for Quality Control)*, 39–48.
Kauffman, A., & Gupta, M. M. (1988). *Fuzzy mathematical models in engineering and management science*. Amsterdam, The Netherlands: North-Holland.
Kwong, C. K., & Bai, H. (2002). A fuzzy AHP approach to the determination of importance weights of customer requirements in quality function deployment. *Journal of Intelligent Manufacturing, 13*, 367–377.
Kwong, C. K., & Bai, H. (2003). Determining the important weights for the customer requirement in QFD using a fuzzy AHP with an extent analysis approach. *IIE Transactions, 35*(7), 619–626.
Lee, H., Kwak, W., & Han, I. (1995). Developing a business performance evaluation system: An analytic hierarchical model. *The Engineering Economist, 40*(4), 343–357.
Liu, J., & Wu, C. (2005). An integrated method for supplier selection in SCM. In *Proceedings of ICSSSM '05 international conference on services systems and services management* (Vol. 1, pp. 617–620).
Mustafa, M. A., & Al-Bahar, J. F. (1991). Project risk assessment using the analytic hierarchy process. *IEEE Transactions on Engineering Management, 38*(1), 46–52.
Power, J. D., & Associates (2007). *Vehicle dependability study, USA*.
Promentilla, M. A. B. (2006). *Development of a multiple criteria decision making method for remedial counter measures of contaminated sites.* Division of Environment and Resources Engineering, Hokkaido University. <http://ws3-er.eng.hokudai.ac.jp/egpsee/alumni/abstracts/Michael.pdf> Accessed 07.07.08.
Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology, 15*, 234–281.
Saaty, T. L. (1980). *The analytic hierarchy process: Planning, priority setting and resource allocation*. New York: McGraw-Hill.
Saaty, T. L. (2000). *Fundamentals of decision making and priority theory with the analytic hierarchy process*. Pittsburg: RWS Publications.
Sharma, B. C., & Gandhi, O. P. (2006). RUL assessment of lube oil using AHP and vector projection approach. *Industrial Lubrication and Tribology, 58*(4), 187–194.
Udo, G. G. (2000). Using analytic hierarchy process to analyze the information technology outsourcing decision. *Industrial Management and Data Systems, 100*(9), 421–429.
Yadav, O. P., & Goel, P. S. (2008). Customer satisfaction driven quality improvement target planning for product development in automotive industry. *International Journal of Production Economics, 113*(2), 997–1011.
Sun, Y., Ma, J., Fan, Z., & Wang, J. (2008). A group decision support approach to evaluate experts for R&D project selection. *IEEE Transactions on Engineering Management, 55*(1), 158–170.
Zadeh, L. A. (1965). Fuzzy sets. *Information and Control, 8*, 338–353.