J Ind Eng Int (2014) 10:51
DOI 10.1007/s40092-014-0051-0

TECHNICAL ARTICLE

Integration of QFD, AHP, and LPP methods in supplier development problems under uncertainty

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Received: 23 July 2013 / Accepted: 20 December 2013 / Published online: 3 April 2014

Abstract Quality function deployment (QFD) is a customer-driven approach, widely used to develop or process new product to maximize customer satisfaction. Last researches used linear physical programming (LPP) procedure to optimize QFD; however, QFD issue involved uncertainties, or fuzziness, which requires taking them into account for more realistic study. In this paper, a set of fuzzy data is used to address linguistic values parameterized by triangular fuzzy numbers. Proposed integrated approach including analytic hierarchy process (AHP), QFD, and LPP to maximize overall customer satisfaction under uncertain conditions and apply them in the supplier development problem. The fuzzy AHP approach is adopted as a powerful method to obtain the relationship between the customer requirements and engineering characteristics (ECs) to construct house of quality in QFD method. LPP is used to obtain the optimal achievement level of the ECs and subsequently the customer satisfaction level under different degrees of uncertainty. The effectiveness of proposed method will be illustrated by an example.

Keywords Quality function deployment (QFD) · Fuzzy · Analytic hierarchy process (AHP) · Linear physical programming (LPP) · Supplier development

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Introduction

The increasing global competition and cooperation and the vertical disintegration of production activities have created the logistical challenge of coordinating the entire supply chain (SC) effectively, upstream to downstream activities (Gebennini et al. 2009). Supply chain management (SCM) integrates suppliers, manufacturers, distributors, and customers to meet final consumer needs and expectations efficiently and effectively (Cox 1999).

Quality function deployment (QFD) was developed by Yoji Akao in the 1960s. The basis of QFD is to obtain and translate customer requirements into engineering characteristics, and subsequently into part characteristics, process plans, and production requirements. This paper is concentrated on the HOQ, which translates customer requirements into the engineering characteristics. By better managing the SC, companies can increase their customers' satisfaction and achieve sustainable business success. SC has different levels and each level can be considered as a customer of the previous level that should be maximized to the customer satisfaction in each level. QFD can be used as a useful method to translate the requirements of each level to the ECs of the previous level. AHP method can be used as a powerful multi-criteria tool to extract the relationships between the requirements of each level and ECs of the previous level. Humans are often uncertain in assigning the evaluation scores in crisp AHP. So FAHP can capture this difficulty. Although QFD implementation extended recently, only a few researchers focused in the supply chain (e.g., Zarei et al. 2011; Hassanzadeh Amin and Razmi 2009).

Satisfying customer requirement is multi-objective optimization problem. Different optimization methods have been applied in the field of QFD to maximize customer satisfaction. Mathematical programming is one of these optimization methods. Linear programming model is used to maximize the overall customer satisfaction (e.g., Chen and Ko 2009; Lai et al. 2007). Park and Kim (1998) used integer programming to optimize product design in the QFD. Chen and Weng (2006) used goal programming to determine the fulfillment levels of the design requirements in the QFD. Delice and Güngör (2009) applied mixed integer linear programming (MILP) to acquire the optimized solution of alternative CRs. Chen and Ko (2010) consider the close link between the four phases using the means-end chain (MEC) concept to build up a set of fuzzy linear programming models to determine the contribution levels of each "how" for customer satisfaction.

Bhattacharya et al. (2010) present a concurrent engineering approach integrating AHP with QFD in combination with cost factor measure (CFM), has been delineated to rank and subsequently select candidate suppliers under multiple, conflicting-in-nature criteria environment within a value-chain framework. Raissi et al. (2012) prioritize engineering characteristic in QFD using fuzzy common set of weight. Lai et al. (2006) used LPP as an effective multi-objective optimization method to optimize QFD. In this paper, we extended Lai et al. (2006) approach using fuzzy numbers instead of the crisp numbers to build HOQ. We used HOQ with triangular fuzzy numbers to extract mathematical model to deal with the fuzziness of the problem to achieve the optimal values of the ECs under different degrees of uncertainty.

Due to the high importance of the SCM, the aim of this paper is to develop a useful approach by integrating fuzzy AHP, fuzzy QFD (FQFD), and LPP to obtain the optimal values of the ECs of the suppliers. Supplier development is an important issue in the context of the SCM. Also, supplier development is a multi-criterion decision-making (MCDM) problem which includes both qualitative and quantitative factors (e.g., Xia and Wu 2007; Chan and Kumar 2007).

In this section literature review of QFD, fuzzy AHP, LPP methods, applying LPP with QFD and fuzzy linear programming are presented. In "Proposed methodology", we present proposed methodology and illustrated it solving a numerical example in "Numerical example". In "Discussion of results", the obtained results are discussed and, finally in "Conclusions" the conclusion is presented.

Quality function deployment

Quality function deployment aims at identifying the customers together with their demands for the product, which are translated into product characteristics. QFD methodology has introduced twofold principles in product development. First, the needs of the customer should be carefully considered during the development process, Secondly, the importance of the different product characteristics should be analyzed and ranked (Bevilacqua et al. 2006).

Many researchers applied QFD to present a new product or to improve product design, which is explained as follows:

Fung et al. (2005) applied an asymmetric fuzzy linear regression approach to estimate the functional relationships for product planning based on QFD. Kahraman et al. (2006) proposed a fuzzy optimization model based on FQFD to determine the product engineering requirements in designing a product. Soota et al. (2011) propose a method to foster product development using combination of QFD and ANP. Sener and Karsak (2011) combined fuzzy linear regression and fuzzy multiple objective programming for setting target levels in the QFD. Based on the Kano's category of design requirements, Chen and Ko (2008) presented a fuzzy nonlinear model to determine the performance level of each design requirements to maximize customer satisfaction. Raharjo et al. (2008) applied AHP to overcome the priorities change over time in the QFD. Sharma and Rawani (2008) develop a post-HoQ model through a well-defined and structured approach to comprehensive matrix and SWOT analysis. Raissi et al. (2011) proposed a novel methodology using common set of weight (CSW) method as a well-known technique in DEA to aggregate each of the requirements expressed by customers and comparisons among the product produced by own company with competitive products.

In the supply chain field, researchers used QFD as an effective decision-making tool, which is explained as follows:

Bottani and Rizzi (2006) proposed a FQFD approach to deploy HOQ to efficiently and effectively improve the logistic process. Bottani (2009) presented an original approach to show the applicability of the QFD methodology to enhance agility of enterprises. Zarei et al. (2011) studied QFD application to identify viable lean enabler for increasing the leanness of food chain. Yousefi et al. (2011) propose an original approach for the management tools selection based on the quality function deployment approach, a methodology that has been successfully adopted in new products development.

Fuzzy analytic hierarchy process (FAHP)

AHP is a decision support tool that can adequately represent qualitative and subjective assessments under the multiple criteria decision-making environment. AHP is strongly connected to human judgment and pairwise comparisons in AHP may cause bias in evaluator's assessment which makes the comparison judgment matrix inconsistent

(Aydogan 2011). Because of this problem, using the fuzzy set theory can solve evaluation bias problem in AHP. Various application of the FAHP can be found for solving MCDM problems. Kahraman et al. (2004) used FAHP to compare catering firms. Chan and Kumar (2007) applied FAHP for solving the global supplier selection problem. Haghighi et al. (2010) applied FAHP to priority of factors that impact electronic banking development in Iran. Rung and Shing (2013) propose a two-stage fuzzy logarithmic preference programming with multi-criteria decision making, to derive the priorities of comparison matrices in the analytic hierarchy process (AHP) and the analytic network process (ANP).

Different methods in the FAHP were employed to extract the weight of criteria base on pairwise comparison matrices. Extent analysis method proposed by Chang (1992, 1996) is a popular approach to determine the weight of criteria (e.g., Kahraman et al. 2004; Haghighi et al. 2010).

Geometric mean technique proposed by Buckley (1985) also was used to define the fuzzy geometric mean and fuzzy weights of each criterion (e.g., Chen et al. 2008; Güngör et al. 2009). After constructing pairwise comparison matrices ($\widetilde{\mathbf{D}}$) according to geometric mean technique using Eq. (5) and (6), we can define the fuzzy weights of each criterion as following:

$$\widetilde{D} = \begin{bmatrix} 1 & \widetilde{d}_{12} \cdots & \widetilde{d}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{d}_{n1} & \widetilde{d}_{n2} \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \widetilde{d}_{12} \cdots & \widetilde{d}_{1n} \\ \vdots & \ddots & \vdots \\ 1/\widetilde{d}_{1n} & 1/\widetilde{d}_{2n} \cdots & 1 \end{bmatrix} \tag{1}$$

where $\widetilde{d}_{ij} = \begin{cases} \text{traingular fuzzy number}, & i \neq j \\ 1 & i = j \end{cases}$

A fuzzy number $\widetilde{d}$ on $\mathbb{R}$ to be a triangular fuzzy number if its membership function $\mu_{\widetilde{d}}(x): \mathbb{R} \to [0, 1]$ can be defined by the following equation:

$$\mu_{\widetilde{d}}(x) = \begin{cases} \dfrac{x - d^l}{d^m - d^l}, & d^l \leq x \leq d^m \\ \dfrac{d^r - x}{d^r - d^m}, & d^m \leq x \leq d^r \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

Let $\widetilde{a}$ and $\widetilde{b}$ be two triangular fuzzy numbers parameterized by the triplet (a_1, a_2, a_3) and (b_1, b_2, b_2), respectively, then the operational laws of these two triangular fuzzy numbers are as follows:

$$\widetilde{a} \oplus \widetilde{b} = (a_1, a_2, a_3) \oplus (b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \tag{3}$$

$$\widetilde{a} \otimes \widetilde{b} = (a_1, a_2, a_3) \otimes (b_1, b_2, b_3) \cong (a_1 \times b_1, a_2 \times b_2, a_3 \times b_3) \tag{4}$$

$$\widetilde{r}_{ij} = \left(\widetilde{d}_{i1} \otimes \cdots \otimes \widetilde{d}_{ij} \otimes \cdots \otimes \widetilde{d}_{in}\right)^{\frac{1}{n}} \tag{5}$$

and the normalized weight of each criterion is obtained as follows:

$$\widetilde{r}'_{ij} = \widetilde{r}_{ij} \otimes \left(\widetilde{r}_{i1} \oplus \cdots \oplus \widetilde{r}_{ij} \oplus \cdots \oplus \widetilde{r}_{in}\right)^{-1} \tag{6}$$

In this paper, the normalized fuzzy weights are used to construct fuzzy HOQ of the QFD.

Linear physical programming (LPP)

Linear physical programming is a multi-objective optimization method that develops an aggregate objective function of the criteria in a piecewise Archimedean goal-programming fashion. The physical programming approach in its nonlinear (general) form was developed by Messac (1996) and in its piecewise linear form, LPP, provides the means for DMs to express his/her priority with respect to each criterion using four classes, i.e., the DM declares each criterion as belonging to one of four distinct classes. Class functions allowed the DMs to express the ranges of differing levels of preference for each criterion. A criterion falls into one of four classes of penalty functions, hereby called class functions, defined as follows:

Class 1S smaller-is-better, i.e., minimization
Class 2S larger-is-better, i.e., maximization
Class 3S value-is-better
Class 4S range-is-better.

Linear physical programming has been used in several diverse applications. Maria et al. (2003) used LPP in production planning. Melachrinoudis et al. (2005) propose a LPP model that enables a decision maker to consider multiple criteria (i.e., cost, customer service and intangible benefits) and to express criteria preferences not in a traditional form of weights, but in ranges of different degrees of desirability.

Tian and Zuo (2006) proposed a multi-objective optimization model using physical programming for redundancy allocation for multi-state series–parallel systems.

Applying LPP with QFD

By applying LPP, the satisfaction level of each customer requirement is classified into one of six different ranges (ideal range, desirable range, tolerable range, undesirable range, highly undesirable range, unacceptable range). According to the proposed methodology by Lai et al. (2006) each engineering characteristic usually needs cost for improvement. Therefore, the last row of the HOQ is the cost index for each engineering characteristic. $X_j = (j = 1, 2, \ldots, q)$ is defined as the value of the engineering characteristic j. The normalized value of engineering characteristic j is defined as:

$$x_j = X_j / \max\{X_j\} \quad \text{and} \quad 0 \le x_j \le 1 \tag{7}$$

Proposed algorithm by Messac et al. (1996) to obtain the weights of the different ranges is as follows:

The value of a class function z_i at the intersection of given ranges is the same for any customer requirement. z_i ($i = 1, 2, \ldots, p$) is loss function defined in LPP, and can be viewed as a loss of customer satisfaction. z_s is defined as the value of class function at range intersection s. It can be expressed mathematically as:

$$z_s \equiv z_i(t_{is}) \tag{8}$$

t_{is} is the limit of different ranges, and s denotes a range. z_s is a constant for all i and $\widetilde{z}^s$ and is defined as:

$$\widetilde{z}^s \equiv z^s - z^{s-1} \quad (2 \le s \le 5) \tag{9}$$

$$z^1 \equiv 0 \tag{10}$$

According to the LPP method, we can define $\widetilde{z}^s$ as:

$$\widetilde{z}^s = \beta(p-1)\widetilde{z}^{s-1}(3 \le s \le 5) \tag{11}$$

where p donates the number of customer requirements and β is the convexity parameter. $\widetilde{t}_{is}$ is defined as:

$$\widetilde{t}_{is} = t_{i(s-1)} - t_{is} \quad (2 \le s \le 5) \tag{12}$$

The importance weight of each customer satisfaction level is given by:

$$w_{is} = \widetilde{z}^s / \widetilde{t}_{is} \quad (2 \le s \le 5) \tag{13}$$

$$w_{i1} = 0 \tag{14}$$

The importance weight of each range for every customer requirement can be calculated as:

$$\widetilde{w}_{is} = w_{is} - w_{i(s-1)} \quad (2 \le s \le 5) \tag{15}$$

And finally by solving the following proposed mathematical model by Lai et al. (2006), the optimal achievement level of the each EC allocated budget to each EC and CRs satisfaction level can be determined.

$$\min_{d_{is}^-, x} \sum_{i=1}^{p} \sum_{s=2}^{5} (\widetilde{w}_{is} d_{is}^-) \tag{16}$$

Subject to:

$$\sum_{j=1}^{q} r_{ij} x_j + d_{is}^- \ge t_{i(s-1)} \quad i = 1, \ldots, p \quad s = 2, \ldots, 5 \tag{17}$$

$$\sum_{j=1}^{q} c_j x_j \le B \tag{18}$$

$$d_{is}^- \ge 0 \quad i = 1, \ldots, p \quad s = 2, \ldots, 5 \tag{19}$$

$$0 \le x_j \le 1 \quad J = 1, \ldots, q \tag{20}$$

The deviational variable, denoted by d_{is}^- can be viewed as the distance from the value of the performance rating of customer requirement i under consideration to $t_{i(s-1)}$, starting from the left-hand side. C_j is the cost of unit improvement of the engineering characteristic, and B is the cost limit for the improvement of all the engineering characteristics.

Fuzzy linear programming

Linear programming (LP) is the optimization technique most frequently applied in real-world problems. Any linear programming model representing real-world situations involves a lot of parameters whose values are assigned by experts, therefore some of these parameters or whole of them can be fuzzy. In this paper, for solving the fuzzy mathematical model we use Jiménez's approach. According to Jiménez (1996), the expected interval (EI) of triangular fuzzy number $\widetilde{d}$ can be defined as follows:

$$EI\left(\widetilde{d}\right) = [E_1^d, E_2^d] = \left[\frac{1}{2}(d^l + d^m), \frac{1}{2}(d^m + d^r)\right] \tag{21}$$

Moreover, according to the ranking method of Jiménez (1996), for any pair of fuzzy numbers $\widetilde{a}$ and $\widetilde{b}$, the degree in which $\widetilde{a}$ is bigger than $\widetilde{b}$ is defined as follows:

$$\mu_M\left(\widetilde{a}, \widetilde{b}\right) = \begin{cases} 0 & \text{if} \quad E_2^a - E_1^b < 0 \\ \dfrac{E_2^a - E_1^b}{E_2^a - E_1^b - (E_1^a - E_2^b)} & \text{if} \quad 0 \in [E_1^a - E_2^b, E_2^a - E_1^b] \\ 1 & \text{if} \quad E_1^a - E_2^b > 0 \end{cases} \tag{22}$$

When $\mu_M\left(\widetilde{a}, \widetilde{b}\right)$ it will demonstrate that $\widetilde{a}$ is bigger than, or equal, to $\widetilde{b}$ at least in a degree α, and it will be represented by $\widetilde{a} \ge_\alpha \widetilde{b}$ for two types of the constraints following as:

$$\widetilde{a}_i x \ge \widetilde{b}_i \quad i = 1, \ldots, m \tag{23}$$

$$\widetilde{a}_i x \le \widetilde{b}_i \quad i = m+1, \ldots, t \tag{24}$$

According to the Jiménez et al. (2007), a decision vector $x \in \Re^n$ is feasible in degree α if $\min_{i=1,\ldots,m} = \{\mu_M(\widetilde{a}_i x, b_i)\} = \alpha$ According to the equation (20), the equation $\widetilde{a}_i x \ge b_i$ is equivalent to the following:

$$\frac{E_2^{a_i x} - E_1^{b_i}}{E_2^{a_i x} - E_1^{a_i x} + E_2^{b_i} - E_1^{b_i}} \ge \alpha \quad i = 1, \ldots, m \tag{25}$$

So equation can be rewritten as follows:

$$[(1-\alpha)E_2^{a_i} + \alpha E_1^{a_i}]x \ge \alpha E_2^{b_i} + (1-\alpha)E_1^{b_i} \quad i = 1, \ldots, m \tag{26}$$

We can do this for $\widetilde{a}_i x \le b_i$, so this equation is equivalent to the following:

Table 1 Triangular fuzzy conversion scale

Linguistic scale	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equal	(1,1,1)	(1,1,1)
Weak	(2/3,1,3/2)	(2/3,1,3/2)
Fairly strong	(3/2,2,5/2)	(2/5,1/2,2/3)
Very strong	(5/2,3,7/2)	(2/7,1/3,2/5)
Absolute	(7/2,4,9/2)	(2/9,1/4,2/7)

$$\left[\alpha E_2^{a_i} + (1-\alpha)E_1^{a_i}\right]x \leq \alpha E_1^{b_i} + (1-\alpha)E_2^{b_i} \quad i = m+1,\ldots,t \tag{27}$$

In this paper, Jiménez's approach is used to solve mathematical model.

The rest of the paper is organized as follows: "Proposed methodology" presents the literature review of QFD, AHP, LPP and applying LPP with QFD. "Numerical example" presents the proposed methodology. In "Discussion of results", the proposed methodology is illustrated by solving a numerical example, and finally in "Conclusions" conclusions is presented.

Proposed methodology

Because of the ambiguity and fuzziness of the real-world problems crisp number cannot deal with the problem carefully. We extended Lai et al. (2006) proposed methodology by combining FAHP method to construct HOQ with the fuzzy numbers. Triangular fuzzy number in Table 1 is used for weighting the ECs with respect to the each CR. Therefore, Eq. (17) is converted to the following equation:

$$\sum_{j=1}^{q} \tilde{r}'_{ij}x_j + d_{is}^- \geq t_{i(s-1)} i = 1,\ldots,p s = 2,\ldots,5 \tag{28}$$

$\tilde{r}'_{ij}$ is triangular fuzzy number, which is obtained by geometric mean method based on the pairwise comparison according to FAHP. We use Jiménez's approach to solve the mathematical model. In Fig. 1, stepwise procedure of the proposed methodology is shown.

Numerical example

We illustrate our proposed methodology step by step by solving an example of supplier development.

Step 1: Information about company requirements and characteristics of the suppliers to satisfy these requirements are collected. Important CRs and ECs are shown in Table 2.

Step 2: Pairwise comparison matrices based on the FAHP method between ECs with respect to the each of the CRs are constructed. For example, the relationship between the engineering characteristics with respect to the cost is shown in Table 3. Similarly, other pairwise comparison matrices can be obtained.

Step 3: Fuzzy relationships of each CR with respect to ECs using Eq. (3)–(6) according to the geometric mean method is determined. For example, the fuzzy relationships between the first requirement and ECs are determined as follows:

$$\tilde{r}_{11} = (\tilde{d}_{11} \otimes \tilde{d}_{12} \otimes \tilde{d}_{13} \otimes \tilde{d}_{14} \otimes \tilde{d}_{15})^{1/5}$$

$$\tilde{r}_{11} = \left((1\times 1\times\cdots\times 2/3)^{1/5}, (1\times 1\times\cdots\times 1)^{1/5}, (1\times 1\times\cdots\times 3/2)^{1/5}\right) = (0.922, 1.149, 1.413)$$

Similarly, we can compute remaining $\tilde{r}_{ij}$, they are as follows:

$$\tilde{r}_{12} = (0.708, 0.871, 1.084)$$
$$\tilde{r}_{13} = (0.979, 1.149, 1.33)$$
$$\tilde{r}_{14} = (0.653, 0.871, 1.176)$$
$$\tilde{r}_{15} = (0.784, 0.871, 1.275)$$

We normalized the calculated weights as follows:

$$\tilde{r}'_{11} = \tilde{r}_{11} \otimes (\tilde{r}_{11} \oplus \tilde{r}_{12} \oplus \tilde{r}_{13} \oplus \tilde{r}_{14} \oplus \tilde{r}_{15})^{-1}$$

$$\tilde{r}'_{11} = (0.922, 1.149, 1.413) \otimes ((0.922, 1.149, 1.413) \oplus\cdots\oplus 0.784, 0.871, 1.275))^{-1} = (0.1, 0.15, .23)$$

The remaining $\tilde{r}'_{ij}$, they are as follows:

$$\tilde{r}'_{12} = (0.1, 0.15, 0.23), \quad \tilde{r}'_{13} = (0.15, 0.21, 0.28),$$
$$\tilde{r}'_{14} = (0.09, 0.15, 0.23), \quad \tilde{r}'_{15} = (0.11, 0.16, 0.29)$$

Step 4: Fuzzy HOQ of QFD is constructed by fuzzy relationships. Table 4 shows the fuzzy HOQ which is built by applying FAHP.

Step 5: Table 5 shows the class function of the CRs and the limit of different ranges of CRs.

Step 6: After determining the limit of different ranges, the weight of the each range of the CRs according to the Messac et al. (1996) $\beta = 1.1$ and $z^2 = 0.1$ (small positive number) is calculated by applying Eq. (8)–(15).

The weights of the different ranges of the cost are as following:

$$\tilde{w}_{12} = 0.001, \quad \tilde{w}_{13} = 1.587, \quad \tilde{w}_{14} = 11.499,$$
$$\tilde{w}_{15} = 16.262$$

The weights of the other customer requirement can be defined similarly.

Fig. 1 Stepwise procedure

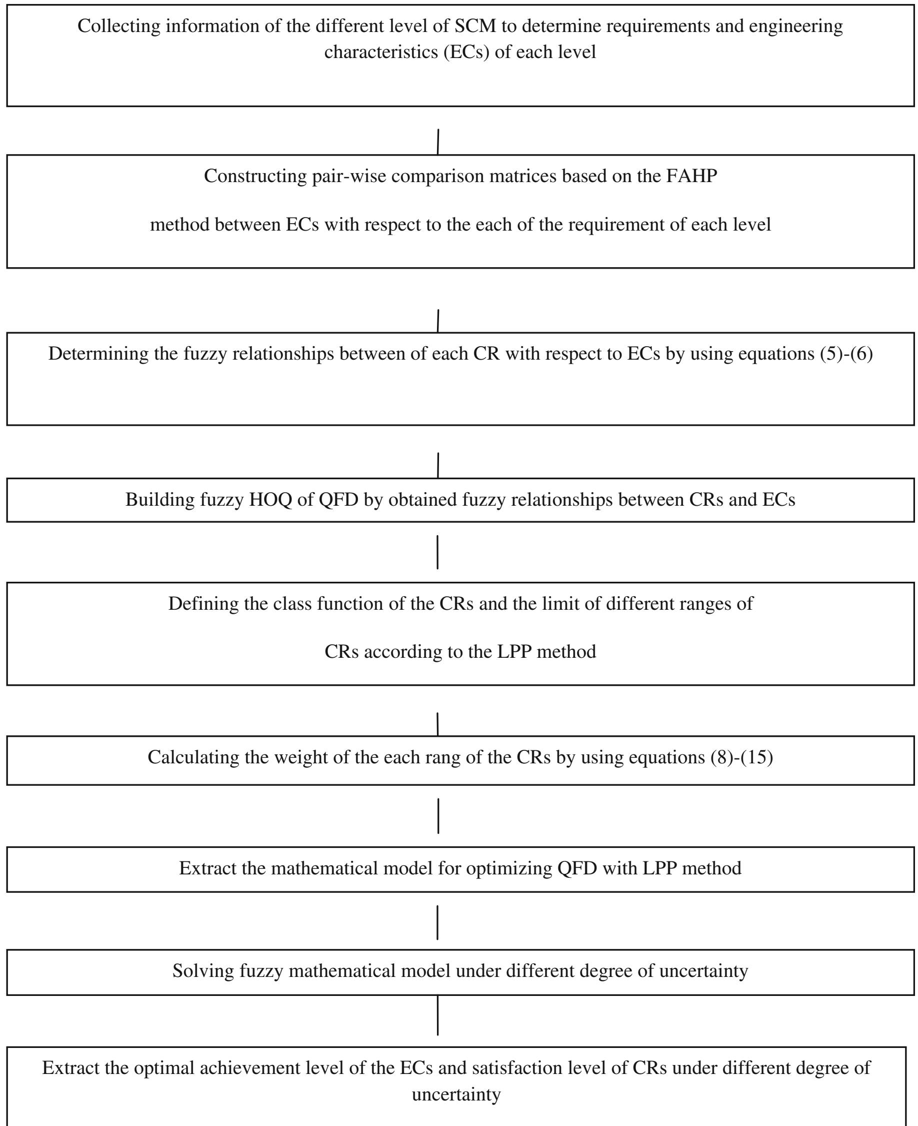

Table 2 Important CRs and ECs

Customer requirements	Engineering characteristics
Cost	EF = experience of the sector
Conformity	IN = capacity for innovation to follow up the customer's evolution in terms of changes in its strategy and market
Punctuality	SQ = quality system certification
Efficacy	FL = flexibility of response to the customer's requests
Lead time	RR = ability to manage orders online (EDI system)

Step 7: By using Eq. (16)–(20), we extract the mathematical model of the problem. We exchange the Eq. 17 with Eq. 29 in our model. Now, we have a model with fuzzy constraints.

Table 3 Pairwise comparison matrix between the engineering characteristics with respect to the cost

Cost	EF	IN	SQ	FL	RR
EF	(1 1 1)	(1 1 1)	(3/2 2 5/2)	(2/3 1 3/2)	(2/3 1 3/2)
IN	(1 1 1)	(1 1 1)	(2/5 ½ 2/3)	(1 1 1)	(2/3 1 3/2)
SQ	(2/5 ½ 2/3)	(3/2 2 5/2)	(1 1 1)	(3/2 2 5/2)	(1 1 1)
FL	(2/3 1 3/2)	(1 1 1)	(2/5 ½ 2/3)	(1 1 1)	(2/3 1 3/2)
RR	(2/3 1 3/2)	(2/3 1 3/2)	(1 1 1)	(2/3 1 3/2)	(1 1 1)

Step 8: By applying the Eq. (27)–(28), the fuzzy model is exchanged to the LP model. We solved the model with different degrees of uncertainty. Tables 6 and 7 show the optimal achievement levels of the ECs and CRs under different degrees of uncertainty which are obtained by solving the model.

Table 4 Fuzzy HOQ of the QFD

	EC_1			EC_2			EC_3			EC_4			EC_5		
CR_1	0.10	0.15	0.23	0.11	0.15	0.22	0.15	0.21	0.28	0.09	0.15	0.23	0.11	0.16	0.29
CR_2	0.10	0.15	0.23	0.11	0.16	0.23	0.12	0.17	0.23	0.11	0.15	0.24	0.12	0.18	0.26
CR_3	0.12	0.19	0.30	0.11	0.17	0.25	0.11	0.15	0.19	0.14	0.21	0.31	0.09	0.14	0.21
CR_4	0.13	0.19	0.27	0.11	0.17	0.27	0.12	0.16	0.21	0.09	0.12	0.15	0.13	0.21	0.31
CR_5	0.12	0.17	0.26	0.12	0.20	0.32	0.10	0.14	0.20	0.14	0.19	0.26	0.09	0.14	0.21

Table 5 Class function of the CRs and the limit of different ranges of CRs

Customer requirements	Class function	The limit of different ranges of CRs according to the LPP method				
		t_1	t_2	t_3	t_4	t_5
Cost	1S	0.14	0.36	0.57	0.71	1
Conformity	2S	1	0.89	0.74	0.47	0.32
Punctuality	2S	1	0.7	0.55	0.3	0.1
Efficacy	2S	1	0.75	0.65	0.5	0.2
Lead time	1S	0	0.29	0.57	0.86	1

Table 6 Optimal achievement levels of the ECs under different values of α

α	Optimal achievement levels of the ECs under different values of α				
	x_1	x_2	x_3	x_4	x_5
0.5	1	1	1	0	1
0.6	1	1	1	0.02	1
0.7	1	1	1	0.17	1
0.8	1	1	0.7	0.44	1
0.9	1	1	0.69	0.29	1
1	1	1	0.69	0.16	1

Discussion of results

The obtained results of this numerical example in Table 6 show that in engineering characteristics, x_3 and x_4 which demonstrate, respectively, quality system certification and flexibility of response to the customer's requests have not been fully achieved in some degree of uncertainty, while the other three characters have been obtained completely in all calculated degree of uncertainty.

The results of Table 7 indicate that the satisfaction level of CR_4 is rather higher than the other four requirements; therefore in this example, efficacy is more important than cost, conformity, punctuality, and lead time. Unlike the existing literature, this method integrates three different concepts such as AHP, QFD, and LLP to achieve the optimal values of the ECs and CRs under different degrees of uncertainty. Therefore, with respect to the company's strategy, managers can use the results of proposed method to improve and develop engineering characteristics of suppliers to meet their requirements.

Table 7 Optimal achievement levels of the CRs under different values of α

α	Satisfaction levels of the CRs under different values of α				
	CR_1	CR_2	CR_3	CR_4	CR_5
0.5	2.17	2.07	2.03	2.29	2.05
0.6	2.18	2.08	2.04	2.29	2.06
0.7	2.25	2.16	2.14	2.35	2.15
0.8	2.18	2.13	2.18	2.3	2.18
0.9	2.11	2.06	2.07	2.24	2.09
1	2.05	1.99	1.99	2.19	2.01

Conclusions

In this paper, we proposed a simple and useful methodology by integrating AHP, QFD, and LPP for supplier development problems under uncertainty conditions. We used fuzzy AHP to determine the relationships between customer's requirements and engineering characteristics for building the relation matrix in the QFD method. Then, applying LPP, we formulated the mathematical model to optimize QFD. Proposed methodology helps decision makers to deal with the vagueness and imprecise involved in the real problems. In addition, it helps them to maximize overall customer satisfaction in supplier development. In addition, the proposed methodology can be used in the product design, product development, process development, and other decision-making problems.

For the future work, we suggest to consider the correlation between engineering characteristics to increase the reliability of the obtained solutions or use the other type of fuzzy programming to obtain optimal achievement level of engineering characteristics and customer satisfaction level.

Conflict of interest The authors declare that there is no conflict of interests.

Authors' contributions All authors ZS, ER and FM, have made adequate effort on all parts of thework necessary for the development of this manuscript according to his/herexpertise. All authors read and approved the final manuscript.

References

Aydogan EK (2011) Performance measurement model for Turkish aviation firms using the rough-AHP and TOPSIS methods under fuzzy environment. Expert Syst Appl 38:3992–3998

Bevilacqua M, Ciarapica FE, Giacchetta G (2006) A fuzzy-QFD approach to supplier selection. J Purch Supply Manag 12:14–27

Bhattacharya A, Geraghty J, Young P (2010) Supplier selection paradigm: an integrated hierarchical QFD methodology under multiple-criteria environment. Appl Soft Comput 10:1013–1027

Bottani E (2009) A fuzzy QFD approach to achieve agility. Int J Prod Econ 119(2):380–391

Bottani E, Rizzi A (2006) Strategic management of logistics service: a fuzzy-QFD approach. Int J Prod Econ 103(2):585–599

Buckley JJ (1985) Fuzzy hierarchical analysis. Fuzzy Sets Syst 17(1):233–247

Chan FTS, Kumar N (2007) Global supplier development considering risk factors using fuzzy extended AHP-based approach. Omega Int J Manag Sci 35:417–431

Chang DY (1992) Extent analysis and synthetic decision, optimization techniques and applications, vol 1. World Scientific, Singapore 352

Chang DY (1996) Applications of the extent analysis method on fuzzy AHP. Eur J Oper Res 95:649–655

Chen LH, Ko WC (2008) A fuzzy nonlinear model for quality function deployment considering Kano's concept. Math Comput Model 48:581–593

Chen LH, Ko WC (2009) Fuzzy linear programming models for new product design using QFD with FMEA. Appl Math Model 33:633–647

Chen LH, Ko WC (2010) Fuzzy linear programming models for NPD using a four-phase QFD activity process based on the means-end chain concept. Eur J Oper Res 201:619–632

Chen LH, Weng MC (2006) An evaluation approach to engineering design in QFD processes using fuzzy goal programming models. Eur J Oper Res 172:230–248

Chen MF, Tseng GH, Ding CG (2008) Combining fuzzy AHP with MDS in identifying the preference similarity of alternatives. Appl Soft Comput 8:110–117

Cox A (1999) Power value and supply chain management. Supply Chain Manag 4(4):167–175

Delice EK, Güngör Z (2009) A new mixed integer linear programming model for product development using quality function deployment. Comput Ind Eng 57:906–912

Fung RYK, Chen Y, Chen L, Tang J (2005) A fuzzy expected value-based goal programming model for product planning using quality function deployment. Eng Optim 37(6):633–647

Gebennini E, Gamberinni R, Manzini R (2009) An integrated production–distribution model for the dynamic location and allocation problem with safety stock optimization. Int J Prod Econ 122:286–304

Güngör Z, Serhadlıoğlu G, Kesen SE (2009) A fuzzy AHP approach to personnel selection problem. Appl Soft Comput 9:641–646

Haghighi M, Divandari A, Keimasi M (2010) The impact of 3D e-readiness on e-banking development in Iran: a fuzzy AHP analysis. Expert Syst Appl 37:4084–4093

Hassanzadeh Amin S, Razmi J (2009) An integrated fuzzy model for supplier management: a case study of ISP selection and evaluation. Expert Syst Appl 36:8639–8648

Jiménez M (1996) Ranking fuzzy numbers through the comparison of its expected intervals. Int J Uncertain Fuzziness Knowl Based Syst 4(4):379–388

Jiménez M, Arenas M, Bilbao A, Rodriguez MV (2007) Linear programming with fuzzy parameters: an interactive method resolution. Eur J Oper Res 177:1599–1609

Kahraman C, Cebeci U, Ruan D (2004) Multi-attribute comparison of catering service companies using fuzzy AHP: the case of Turkey. Int J Prod Econ 87:171–184

Kahraman C, Ertay T, Büyüközkan G (2006) A fuzzy optimization model for QFD planning process using analytic network process. Eur J Oper Res 171:390–411

Lai X, Xie M, Tan KC (2006) QFD optimization using linear physical programming. Eng Optim 38(5):593–607

Lai X, Xie M, Tan KC (2007) Optimizing product design using quantitative quality function deployment: a case study. Qual Reliab Eng Int 23:45–572

Maria A, Mattson CA, Ismail-Yahaya A, Messac A (2003) Linear physical programming for production optimization. Eng Optim 35(1):19–37

Melachrinoudis E, Messac A, Min H (2005) Consolidating a warehouse network: a physical programming approach. Int J Prod Econ 97:1–17

Messac A (1996) Physical programming: effective optimization for computational design. AIAA J 34(1):149–158

Messac A, Gupta SM, Akbulut B (1996) Linear physical programming: a new approach to multiple objective optimization. Trans Oper Res 8:39–59

Park T, Kim K (1998) Determination of an optimal set of design requirements using house of quality. J Oper Manag 16:569–581

Raharjo H, Brombacher AC, Xie M (2008) Dealing with subjectivity in early product design phase: a systematic approach to exploit Quality Function Deployment potentials. Comput Ind Eng 55:253–278

Raissi S, Izadi M, Saati S (2011) A novel method on customer requirements preferences based on common set of weight. Aust J Basic Appl Sci 5(6):1544–1552

Raissi S, Izadi M, Saati S (2012) Prioritizing engineering characteristic in QFD using fuzzy common set of weight. Am J Sci Res 49:34–49

Rung YuJ, Shing WY (2013) Fuzzy analytic hierarchy process and analytic network process: an integrated fuzzy logarithmic preference programming. Appl Soft Comput 13:1792–1799

Sener Z, Karsak EE (2011) A combined fuzzy linear regression and fuzzy multiple objective programming approach for setting target levels in quality function deployment. Expert Syst Appl 38:3015–3022

Sharma JR, Rawani AM (2008) Quality function deployment: integrating comprehensive matrix and SWOT analysis for effective decision making. J Ind Eng Int 4(6):19–31

Soota T, Singh H, Mishra RC (2011) Fostering product development using combination of QFD and ANP: A case study. J Ind Eng Int 7(14):29–40

Tian Z, Zuo MJ (2006) Redundancy allocation for multi-state systems using physical programming and genetic algorithms. Reliab Eng Syst Saf 91:1049–1056

Xia W, Wu Z (2007) Supplier selection with multiple criteria in volume discount environments. Omega 35(5):494–504

Yousefi S, Mohammadi M, Haghighat Monfared J (2011) Selection effective management tools on setting European Foundation for Quality Management (EFQM) model by a quality function deployment (QFD) approach. Expert Syst Appl 38:9633–9647

Zarei M, Fakhrzad MB, Jamali Paghaleh M (2011) Food supply chain leanness using a developed QFD model. J Food Eng 102:25–33