J. Soc. Korea Ind. Syst. Eng Vol. 39, No. 2 : 138-149, June 2016
http://dx.doi.org/10.11627/jkise.2016.39.2.138
ISSN : 2005-0461(print)
ISSN : 2287-7975(online)

Using Fuzzy Numbers in Quality Function Deployment Optimization

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QFD 최적화에서 퍼지 넘버의 이용

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Quality function deployment (QFD) is a widely adopted customer-oriented product development methodology by translating customer requirements (CRs) into technical attributes (TAs), and subsequently into parts characteristics, process plans, and manufacturing operations. A main activity in QFD planning process is the determination of the target levels of TAs of a product so as to achieve a high level of customer satisfaction using the data or information included in the houses of quality (HoQ). Gathering the information or data for a HoQ may involve various inputs in the form of linguistic data which are inherently vague, or human perception, judgement and evaluation for the information and data. This research focuses on how to deal with this kind of impreciseness in QFD optimization. In this paper, it is assumed as more realistic situation that the values of TAs are taken as discrete, which means each TA has a few alternatives, as well as the customer satisfaction level acquired by each alternative of TAs and related cost are determined based on subjective or imprecise information and/or data. To handle these imprecise information and/or data, an approach using some basic definitions of fuzzy sets and the signed distance method for ranking fuzzy numbers is proposed. An example of a washing machine under two-segment market is provided for illustrating the proposed approach, and in this example, the difference between the optimal solution from the fuzzy model and that from the crisp model is compared as well as the advantage of using the fuzzy model is drawn.

Keywords : Quality Function Deployment, Impreciseness, Fuzzy Sets, Signed Distance Ranking

1. Instroduction

Quality function deployment (QFD) is a widely adopted customer-oriented product development methodology by analyzing customer requirements (CRs) [1]. It is the basic concept of QFD to make use of a set of charts called the houses of quality (HoQ) to translate CRs into technical attributes (TAs) and subsequently into parts characteristics, process plans, and manufacturing operations [11]. In the stage of translating CRs into TAs, a HoQ typically includes information on the relationship between CRs and TAs, and among TAs and benchmarking data [16]. Based upon the information contained in a HoQ, the optimal levels of the TAs of a product to achieve a high level of customer satisfaction is determined, which is a main activity in QFD planning process. Many studies have been carried out in the field of this kind of QFD optimization.

In this paper, however, we are not proposing a new solution approach for selecting the optimal set of the TAs in the QFD planning process. Instead, we are interested in studying how to deal with imprecise data that would occur in practical circumstances. Gathering the information and/or data for a HoQ

Received 14 March 2016; Finally Revised 14 June 2016;
Accepted 17 June 2016
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may involve various inputs in the form of linguistic data which are inherently vague, or human perception, judgement and evaluation on the information and/or data [2]. To handle the impreciseness, many researches that combine fuzzy approaches with mathematical programming for QFD optimization have been carried out [3-10, 12-14, 16, 19, 20-23, 26, 27].

On the other hand, a review of the QFD analysis related literature reveals that in many studies, the values of TAs are assumed to be continuous. In the real world applications, however, they are often taken as discrete, which means each TA has a few alternatives [9, 17, 25]. Then, experienced engineers usually assign a single value to the customer satisfaction level achieved by each alternative for TAs and related costs, respectively rather than clarify the precise relationships among them. However, these decisions are usually made based on their subjective experiences and/or vague (fuzzy) information. Thus, in this study, it is assumed that customer satisfaction level and cost for each TA's alternative are imprecise, which may be in the vicinity of a fixed value, or substantially less than or greater than a fixed value. We will focus on how to deal with the imprecise information and/or data necessary for QFD optimization. To deal with this kind of imprecise data, we use some fundamental fuzzy set theory and the signed distance ranking method [15, 18, 28] to model and solve the problem considered in this study.

The proposed approach in this research can be depicted briefly as follows. Consider the cost for an alternative of TAs. Since each cost for TAs, c_i, $\forall i$, is imprecise, the engineers should determine an interval $[c_i - \Delta_{i1}, c_i + \Delta_{i2}]$, $0 \leq \Delta_{i1} < c_i$ and $0 < \Delta_{i2}$, to represent an acceptable range for the cost of each TA. This range is interpreted as follows. If an estimate of the cost is exactly c_i, then the acceptable grade for that cost will be 1; otherwise, the acceptable grade will get smaller when an estimate is approaching one of the ends of the interval, i.e., $c_i - \Delta_{i1}$ or $c_i + \Delta_{i2}$. Accordingly, the engineers need to determine an appropriate estimate for each cost from the interval $[c_i - \Delta_{i1}, c_i + \Delta_{i2}]$. This leads to the use of fuzzy numbers, $\tilde{c}_i = (c_i - \Delta_{i1}, c_i, c_i + \Delta_{i2})$, for the problem considered in this study. Obviously, the membership grade of a fuzzy number in the fuzzy set corresponds to the acceptable grade of an estimate in a given interval. Thus, after defuzzifying the fuzzy number $\tilde{c}_i$ using the proposed ranking method, we obtain an estimate for each cost for TAs' alternatives in the fuzzy sense, for example, c_i^*, which is in the interval $[c_i - \Delta_{i1}, c_i + \Delta_{i2}]$. Similarly, this fuzzy logic can be applied to each customer satisfaction level achieved by TAs' alternatives which is also assumed to be imprecise in this paper and we can obtain an estimate for each customer satisfaction level for TAs' alternatives, for example, s_i^*, $\forall i$. Then we use c_i^* and s_i^* as the cost and the customer satisfaction level for TA i for all i, respectively, to make the fuzzy model crisp, and then use the approach for solving the crisp problem to solve the fuzzy model. The advantage of the proposed fuzzy model in this study is that it is much easier to specify a range value than to give an exact value for each imprecise cost and customer satisfaction level of TAs' alternatives.

The remaining of this paper is organized as follows. The second section introduces the crisp model and the model with fuzzy numbers including some basic definitions of fuzzy sets and the signed distance method for ranking fuzzy numbers. In the third section, an example is shown to illustrate the proposed approach. Finally, conclusions are drawn in the last section.

2. Model

Concisely speaking, the model is based on one proposed by Yoo [25], and in this paper, it extends to fuzzy model. In [25], the problem of determining the optimal levels of the TAs in QFD under a multi-segment product market is formulated as an optimization model. It is supposed that a product has I CRs and J TAs, and the product market is partitioned into T market segments. Based on the information provided in HoQs, an optimization model is built with the objective of maximizing the overall customer satisfaction (OCS) within limited budget under a multi-segment market. In this research, it is assumed that the two data in the above model, customer satisfaction level and cost for each TA's alternative, are imprecise. To deal with these imprecise data, an approach using fundamental fuzzy set theory and the signed distance ranking method is proposed to build the fuzzy optimization model.

Section 2.1, 2.2, and 2.3 briefly introduce the model built in [25]. In section 2.4, the proposed approach in this study to handle the imprecise data is illustrated.

2.1 Modelling the OCS for a Product Market

For market segment t, we can obtain the relative importance of CR i from the other CRs, w_{it} ($0 \leq w_{it} \leq 1$ and $\sum_{i=1}^{I} w_{it} = 1$), and the relationship between CR i and TA j, r_{ijt} ($0 \le r_{ijt} \le 1$ and $\sum_{j=1}^{J} r_{ijt} = 1$). Since the values of TAs are assumed to be discrete in this research, TA_{jkt} represents alternative k of TA j in market segment t. s_{ijkt} refers to the customer satisfaction level for CR i acquired by TA_{jkt}. S_{jkt} means the overall customer satisfaction for CRs in market segment t achieved by TA_{jkt}. Then, S_{jkt} can be defined as the following

$$S_{jkt} = \sum_{i=1}^{I} w_{it} r_{ijt} s_{ijkt} x_{jkt} \tag{1}$$

where x_{jkt} is equal to 1 if alternative k of TA j in market segment t, TA_{jkt}, is selected, and it is equal to 0 otherwise. The overall customer satisfaction for the customers in market segment t, OCS_t, can be expressed as

$$OCS_t = \sum_{j=1}^{J}\sum_{k=1}^{K} S_{jkt} = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{i=1}^{I} w_{it} r_{ijt} s_{ijkt} x_{jkt} \tag{2}$$

Assuming that the overall customer satisfaction of the whole market, OCS_w, is the weighted sum of each OCS_t over the multi-segment market, the objective function of this optimization problem can be formulated as

$$OCS_w = \sum_{t=1}^{T} \xi_t OCS_t = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{i=1}^{I} \xi_t w_{it} r_{ijt} s_{ijkt} x_{jkt} \tag{3}$$

where ξ_t is the normalized weight of the importance of market segment t ($0 \le \xi_t \le 1$ and $\sum_{t=1}^{T} \xi_t = 1$).

If the number of customers in market segment t is estimated according to historical sales data of a firm, ξ_t can be obtained as

$$\xi_t = q_t / \sum_{t=1}^{T} q_t \tag{4}$$

where q_t is the estimated number of customers in market segment t.

2.2 Formulating the Development Budget Constraint

Various resources including technical engineers, advanced equipment, tools and other facilities are required to support the design of a new product. From the standpoint of strategic planning, these types of resources can be represented in financial terms. Assuming that the cost of attaining alternative k of TA j in market segment t, TA_{jkt}, is c_{jkt} and the cost function for achieving the degree of attainment of TA_{jkt} is scaled linearly to the degree of x_{jkt}, the budget constraint can be described as

$$\sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{k=1}^{K} c_{kjt} x_{jkt} \le B \tag{5}$$

where B is the budget for the development of the product over the multi-segment market.

2.3 Optimization Model

The problem of selecting a set of alternatives of TAs for each segment in a multi-segment market so as to maximize the OCS of the multi-segment market while not exceeding budget available for the multi-segment market can be formulated as a multiple choice 0-1 knapsack problem.

Problem (P)

$$\max \; OCS_w = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{i=1}^{I} \xi_t w_{it} r_{ijt} s_{ijkt} x_{jkt} \tag{6}$$

$$\text{s.t.} \quad \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{k=1}^{K} c_{jkt} x_{jkt} \le B \tag{7}$$

$$\sum_{k=1}^{K} x_{jkt} = 1 \qquad \text{for all } j,\ t \tag{8}$$

$$x_{jkt} \in \{0, 1\} \qquad \text{for all } j,\ k,\ t \tag{9}$$

In the formulation of Problem (P), the objective function (6) maximizes the OCS for the multi-segment market; the budget constraint (7) indicates that the capital consumption by the selected alternatives cannot exceed the available budget for the multi-segment market; the alternative selection constraint set (8) forces the problem to choose one and only one alternative for each TA in any market segment; and the constraint set (9) imposes the integrality of the decision variables.

2.4 Optimization Model with Fuzzy Numbers

As mentioned previously in this paper, the customer satisfaction level for CR i acquired by TA_{jkt}, s_{ijkt}, and related cost, c_{jkt}, are assumed to be imprecise since these data are usually determined based on the subjective judgement and/or vague knowledge of the experienced engineers.

Now, consider s_{ijkt}. The engineers should determine acceptable ranges of values for each s_{ijkt}, which is an interval $[s_{ijkt} - \Delta_{ijkt1}, s_{ijkt} + \Delta_{ijkt2}]$, $0 \le \Delta_{ijkt1} \le s_{ijkt}$ and $0 \le \Delta_{ijkt2}$. Then, they choose a value from the interval $[s_{ijkt} - \Delta_{ijkt1},$

$s_{ijkt}+\Delta_{ijkt2}]$ as an estimate of each s_{ijkt}. We say that the acceptable grade is 1 if the estimate is exactly s_{ijkt}; otherwise, the acceptable grade will get smaller when the estimate approaches either $s_{ijkt}-\Delta_{ijkt1}$ or $s_{ijkt}+\Delta_{ijkt2}$. It is clear that the acceptable grade for an estimate in an interval corresponds to the membership grade of a fuzzy number in the fuzzy set. Thus, this leads to the use of fuzzy numbers.

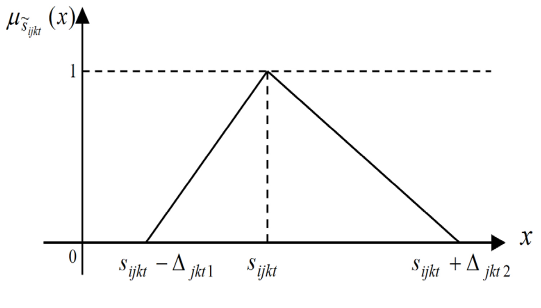
Let $\tilde{s}_{jkt}$ be the fuzzy number denoted by

$$\tilde{s}_{ijkt}=(s_{ijkt}-\Delta_{ijkt1},\ s_{ijkt},\ s_{ijkt}+\Delta_{ijkt2}),\quad 0\le\Delta_{ijkt1}<s_{ijkt},\ 0<\Delta_{ijkt2}\quad \text{for all } i,\ j,\ k,\ t \tag{10}$$

The membership function of $\tilde{s}_{ijkt}$ is as shown below :

$$\mu_{\tilde{s}_{ijkt}}(x)=\begin{cases}\dfrac{x-s_{ijkt}+\Delta_{ijkt1}}{\Delta_{ijkt1}}, & s_{ijkt}-\Delta_{ijkt1}\le x\le s_{ijkt}\\ \dfrac{s_{ijkt}+\Delta_{ijkt2}-x}{\Delta_{ijkt2}}, & s_{ijkt}\le x\le s_{ijkt}+\Delta_{ijkt2},\\ 0, & \text{otherwise}\end{cases} \tag{11}$$

<Figure 1> shows that when an estimate x equals s_{ijkt}, the membership grade of x in $\tilde{s}_{ijkt}$ is 1. However, the more away from the position of s_{ijkt} an estimate x is, the less membership grade of x in $\tilde{s}_{ijkt}$ is obtained. The representation of imprecise data as fuzzy numbers is useful when those data are used in fuzzy systems.



<Figure 1> The Fuzzy Number $\tilde{s}_{ijkt}$

Now, consider the problem of ranking fuzzy numbers. We will use the signed distance ranking method, which was defined in [24] for ranking the fuzzy numbers in this research.

Definition 1 : The signed distance of b is defined by $d^*(b, 0)=b$, $b, 0\in R$.

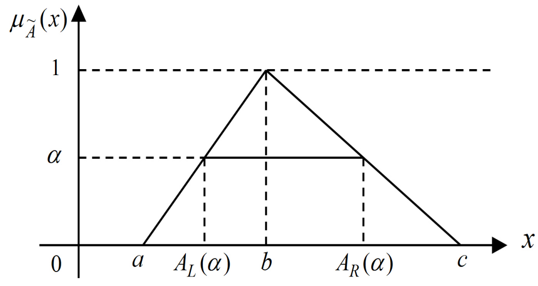
The signed distance is described as follows. If $b>0$, b lies to the right of the origin 0 and the distance between b and 0 is denoted by $d^*(b, 0)=b$. Similarly, if $b<0$, b lies to the left of the origin 0 and the distance between b and 0 is denoted by $-d^*(b, 0)=-b$. In summary, $d^*(b, 0)$ stands for the signed distance of b measured from the origin 0.

We can see in <Figure 2> that a α-cut of the fuzzy number $\tilde{A}=(a, b, c)$ is an interval $[A_L(\alpha), A_R(\alpha)]$, $0\le\alpha\le 1$, where $A_L(\alpha)$ and $A_R(\alpha)$ are the left endpoint and the right endpoint of the α-cut, respectively. The membership function of $\tilde{A}=(a, b, c)$ is as shown below :

$$\mu_{\tilde{A}}(x)=\begin{cases}(x-a)/(b-a), & a\le x\le b,\\ (c-x)/(c-b), & b\le x\le c,\ a<b<c,\\ 0, & \text{otherwise}.\end{cases} \tag{12}$$

From (12) we have that $A_L(\alpha)=a+(b-a)\alpha$ and $A_R(\alpha)=c-(c-b)\alpha$, where $A_L(\alpha)$ and $A_R(\alpha)$ are the signed distances measured from 0. From Definition 1, we have that $d^*(A_L(\alpha), 0)=A_L(\alpha)$ and $d^*(A_R(\alpha), 0)=A_R(\alpha)$, $0\le\alpha\le 1$. Hence, the signed distance of the interval $[A_L(\alpha), A_R(\alpha)]$ is defined by $d^*([A_L(\alpha), A_R(\alpha)], 0)=\frac{1}{2}[d^*(A_L(\alpha), 0)+d^*(A_R(\alpha), 0)]=\frac{1}{2}[A_L(\alpha), A_R(\alpha)]=\frac{1}{2}[a+c+(2b-a-c)\alpha]$. Since the function for α is continuous over the interval, the integration can be used to obtain the mean of the signed distance, i.e. $\int_0^1 d^*([A_L(\alpha), A_R(\alpha)], 0)d\alpha=\frac{1}{2}\int_0^1[a+c+(2b-a-c)\alpha]d\alpha=\frac{1}{4}(2b+a+c)$. In addition, for each $\alpha\in[0, 1]$, there is a one-to-one mapping between the interval $[A_L(\alpha), A_R(\alpha)]$ and $[A_L(\alpha)_\alpha, A_R(\alpha)_\alpha]$ as shown in <Figure 2>, where $[A_L(\alpha)_\alpha, A_R(\alpha)_\alpha]$ is a fuzzy set on $R=(-\infty, \infty)$, $A_L(\alpha), A_R(\alpha)\in R$ and $0\le\alpha\le 1$, which is called a level α fuzzy interval, if its membership function is as given below :

$$\mu_{[A_L(\alpha)_\alpha,\ A_R(\alpha)_\alpha]}(x)=\begin{cases}\alpha, & A_L(\alpha)\le x\le A_R(\alpha)\\ 0, & \text{otherwise}\end{cases} \tag{13}$$



<Figure 2> A α-cut of Fuzzy Number $\tilde{A}$

Thus, we have Definition 2 as follows.

Definition 2 : Let $\widetilde{A}=(a, b, c)\in F_N$, where $F_N=\{(a, b, c) \mid \forall a \le b \le c,\ a, b, c \in R\}$. The signed distance of $\widetilde{A}$ measured from $\tilde{0}_1$(y-axis) is defined by

$$d(\widetilde{A}, \tilde{0}_1)=\int_0^1 d([A_L(\alpha)_\alpha, A_R(\alpha)_\alpha], \tilde{0}_1)d\alpha$$
$$=\frac{1}{2}\int_0^1 [A_L(\alpha)+A_R(\alpha)]d\alpha$$
$$=\frac{1}{4}(2b+a+c) \quad (14)$$

Thus, after defuzzyfying the fuzzy number $\tilde{s}_{ijkt}$ by Definition 2, we obtain an estimate of the customer satisfaction level for CR i acquired by TA_{jkt} in the fuzzy sense from the interval $[s_{ijkt}-\Delta_{ijkt1}, s_{ijkt}+\Delta_{ijkt2}]$ as follows :

$$s^*_{ijkt}=d(\tilde{s}_{ijkt}, \tilde{0}_1)=s_{ijkt}+\frac{1}{4}(\Delta_{ijkt2}-\Delta_{ijkt1}) \quad (15)$$

The engineers can then make use of this equation to obtain a value as an estimate of the customer satisfaction level for CR i acquired by TA_{jkt} for solving the imprecise data problem.

Similarly, when fuzzifying the cost of TA_{jkt}, c_{jkt}, we obtain as follows :

$$\tilde{c}_{jkt}=(c_{jkt}-\Delta_{jkt1}, c_{jkt}, c_{jkt}+\Delta_{jkt2}),$$
$$0 \le \Delta_{jkt1} < c_{jkt},\ 0 < \Delta_{jkt2} \quad \text{for all } j,\ k,\ t \quad (16)$$

The membership function of $\tilde{c}_{jkt}$ is as shown below :

$$\mu_{\tilde{c}_{jkt}}(x)=\begin{cases} \dfrac{x-c_{jkt}+\Delta_{jkt1}}{\Delta_{jkt1}}, & c_{jkt}-\Delta_{jkt1} \le x \le c_{jkt}, \\ \dfrac{c_{jkt}+\Delta_{jkt2}-x}{\Delta_{jkt2}}, & c_{jkt} \le x \le c_{jkt}+\Delta_{jkt2}, \\ 0, & \text{otherwise} \end{cases} \quad (17)$$

From definition 2, we obtain an estimate of the cost of TA_{jkt} in the fuzzy sense from the interval $[c_{jkt}-\Delta_{jkt1}, c_{jkt}+\Delta_{jkt2}]$ as follows :

$$c^*_{jkt}=d(\tilde{c}_{jkt}, \tilde{0}_1)=c_{jkt}+\frac{1}{4}(\Delta_{jkt2}-\Delta_{jkt1}) \quad (18)$$

The engineers can also obtain a value as an estimate of the cost of TA_{jkt} by using equation (18) to solve the fuzzy problem considered in this study.

From Problem (P) and Definition 2, the defuzzified Problem (P) in the fuzzy sense is formulated as follows :

Problem (Q)

$$\max\ OCS_w=\sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{i=1}^{I}\xi_t w_{it} r_{ijt} s^*_{ijkt} x_{jkt} \quad (19)$$

$$\text{s.t.} \quad \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{k=1}^{K} c^*_{jkt} x_{jkt} \le B \quad (20)$$

$$\sum_{k=1}^{K} x_{jkt}=1 \quad \text{for all } j,\ t \quad (21)$$

$$x_{jkt}\in\{0, 1\} \quad \text{for all } j,\ k,\ t \quad (22)$$

where,

$$s^*_{ijkt}=s_{ijkt}+\frac{1}{4}(\Delta_{ijkt2}-\Delta_{ijkt1}),\ 0 \le \Delta_{ijkt1} < s_{ijkt},\ 0 \le \Delta_{ijkt2},$$

$$c^*_{jkt}=c_{jkt}+\frac{1}{4}(\Delta_{jkt2}-\Delta_{jkt1}),\ 0 \le \Delta_{jkt1} < c_{jkt},\ 0 \le \Delta_{jkt2},$$

3. An Illustrative Example

In order to illustrate the application of the proposed approach in this research, a simple example modified from Yoo. (2015) is used [25]. The problem for the application is to determine the optimal levels of the TAs of a washing machine according to the CRs in the two market segments, in which it is assumed that customer satisfaction level and cost for each TA's alternative are imprecise. To handle these imprecise data and/or information, the proposed approach in this research using some basic definitions of fuzzy sets and the signed distance method for ranking fuzzy numbers are applied to the example. To compare the results from this example with the one from the example used in [25], fuzzy and crisp numbers for customer satisfaction level and cost for each TA's alternative are used for this example.

According to the market survey in [25], the customers of the washing machine for the two market segments have five CRs as their biggest concern for the product which are "thorough washing", "quiet washing", "thorough rinsing", "less damage to clothes" and "short washing time". From the viewpoint of engineer's design of the washing machine, five TAs are also identified to satisfy the five CRs, i.e. "washing quality (%)", "noise level (dB)", "washing time (min)", "rinsing quality (%)" and "clothes damage rate (%)." In this example, each TA has three alternatives. The relationship between CRs and TAs, the relative importance of CRs, and the alternatives of each TA and corresponding customer satisfaction information for the market segment 1 and 2 are showed in the HoQs in <Table 1> and <Table 2>, respectively. Since the customer satisfaction level for each TA's alternative are assumed to be imprecise in this example, fuzzy numbers are used. To put these fuzzy numbers in the HoQ template, the range of the customer satisfaction levels for each alternative of TAs determined by the experienced engineers, Δ_{ijkt1} and Δ_{ijkt2} for s_{ijkt1}, for all *i*, *j*, *k*, *t*, as well as the estimates of the customer satisfaction levels obtained by using $s^*_{ijkt} = s_{ijkt} + \frac{1}{4}(\Delta_{ijkt2} - \Delta_{ijkt1})$, for all *i*, *j*, *k*, *t*, are also shown in <Table 1> and <Table 2> for the two segments, respectively. <Table 1> and <Table 2> also include the crisp numbers for the customer satisfaction level for each TA's alternative for the two segments, respectively.

The cost information related to the TAs' alternatives and the total budget for the two market segments are given as follows. As the costs for each TA's alternative are also assumed to be imprecise in this example, the range for these costs, Δ_{jkt1} and Δ_{jkt2} for c_{jkt}, for all *j*, *k*, *t*, as well as the estimates of the costs obtained by using $c^*_{jkt} = c_{jkt} + \frac{1}{4}$ $(\Delta_{jkt2} - \Delta_{jkt1})$ for all *j*, *k*, *t*, are shown in <Table 3> and <Table 4> for the two segments, respectively including the crisp numbers for c_{jkt}, for all *j*, *k*, *t*,. The accumulative customer satisfaction level achieved by each TA alternative for the two market segments is also shown in <Table 3> and <Table 4> for both cases of crisp numbers and fuzzy numbers. The total budget is assumed to be 24. We also assume that the numbers of customers in the two market segments, q_1 and q_2, were estimated as 12,000 and 9,000, respectively. These data are used to represent the importance of the two market segments.

Based on these data given in this example, Problem (*P*) and Problem (*Q*) which are the crisp model in [25] and the fuzzy model, respectively are formulated as follows :

Problem (*P*)

$$\begin{aligned}
\max\ & 0.1475x_{111}+0.1716x_{121}+0.1823x_{131}+0.0769x_{211}+0.0550x_{221} \\
& +0.0335x_{231}+0.0497x_{311}+0.0425x_{321}+0.0357x_{331}+0.1444x_{411} \\
& +0.1130x_{421}+0.0766x_{431}+0.0829x_{511}+0.0819x_{521}+0.0782x_{531} \\
& +0.0945x_{112}+0.0994x_{122}+0.1036x_{132}+0.0014x_{212}+0.0020x_{222} \\
& +0.0029x_{232}+0.0593x_{312}+0.0612x_{322}+0.0635x_{332}+0.0660x_{412} \\
& +0.0792x_{422}+0.1132x_{432}+0.0903x_{512}+0.0964x_{522}+0.1083x_{532} \\
\text{s.t.}\ & 3x_{111}+4x_{121}+5x_{131}+5x_{211}+3x_{221}+2x_{231}+4x_{311}+2x_{321} \\
& +1x_{331}+3x_{411}+2x_{421}+1x_{431}+4x_{511}+2x_{521}+1x_{531}+3x_{112} \\
& +4x_{122}+5x_{132}+3x_{212}+4x_{222}+5x_{232}+1x_{312}+2x_{322}+3x_{332} \\
& +1x_{412}+2x_{422}+4x_{432}+1x_{512}+2x_{522}+3x_{532} \le 24 \\
& x_{111}+x_{121}+x_{131} = 1 \\
& x_{211}+x_{221}+x_{231} = 1 \\
& x_{311}+x_{321}+x_{331} = 1 \\
& x_{411}+x_{421}+x_{431} = 1 \\
& x_{511}+x_{521}+x_{531} = 1 \\
& x_{112}+x_{122}+x_{132} = 1 \\
& x_{212}+x_{222}+x_{232} = 1 \\
& x_{312}+x_{322}+x_{332} = 1 \\
& x_{412}+x_{422}+x_{432} = 1 \\
& x_{512}+x_{522}+x_{532} \le\ = 1 \\
& x_{jkt} \in \{0, 1\} \quad \text{for all } j,\ k,\ t
\end{aligned}$$

Problem (*Q*)

$$\begin{aligned}
\max\ & 0.153x_{111}+0.1700x_{121}+0.1820x_{131}+0.07693x_{211}+0.05365x_{221} \\
& +0.04082x_{231}+0.0499x_{311}+0.0427x_{321}+0.0363x_{331}+0.1447x_{411} \\
& +0.1144x_{421}+0.0823x_{431}+0.0815x_{511}+0.0800x_{521}+0.0793x_{531} \\
& +0.0950x_{112}+0.0988x_{122}+0.1043x_{132}+0.0015x_{212}+0.0021x_{222} \\
& +0.0029x_{232}+0.0598x_{312}+0.0614x_{322}+0.0644x_{332}+0.0677x_{412} \\
& +0.0804x_{422}+0.1130x_{432}+0.0867x_{512}+0.0927x_{522}+0.1027x_{532} \\
\text{s.t.}\ & 2.7425x_{111}+3.9825x_{121}+5.0575x_{131}+5.0625x_{211}+3.0825x_{221} \\
& +1.775x_{231}+4.07x_{311}+2.23x_{321}+1.2425x_{331}+2.6025x_{411} \\
& +2.36x_{421}+1.155x_{431}+4.21x_{511}+2.08x_{521}+1.035x_{531} \\
& +3.025x_{112}+4.495x_{122}+4.58x_{132}+2.84x_{212}+3.585x_{222} \\
& +5.26x_{232}+1.1225x_{312}+1.9425x_{322}+2.595x_{332}+0.8475x_{412} \\
& +1.835x_{422}+3.7075x_{432}+1.225x_{512}+2.1775x_{522} \\
& +2.645x_{532} \le 24 \\
& x_{111}+x_{121}+x_{131} = 1 \\
& x_{211}+x_{221}+x_{231} = 1 \\
& x_{311}+x_{321}+x_{331} = 1 \\
& x_{411}+x_{421}+x_{431} = 1 \\
& x_{511}+x_{521}+x_{531} = 1 \\
& x_{112}+x_{122}+x_{132} = 1 \\
& x_{212}+x_{222}+x_{232} = 1 \\
& x_{212}+x_{222}+x_{232} = 1 \\
& x_{312}+x_{322}+x_{332} = 1 \\
& x_{412}+x_{422}+x_{432} = 1 \\
& x_{512}+x_{522}+x_{532} = 1 \\
& x_{jkt} \in \{0, 1\} \quad \text{for all } j,\ k,\ t
\end{aligned}$$

<Table 1> The HoQ for Market Segment 1

Customer Requirement	Weight	Washing Quality (%)					Noise Level (dB)					Washing Time (min)					Rinsing Quality (%)					Clothes Damage Rate (%)				
		Relationship bet CR *i* & TA *j*					Relationship bet CR *i* & TA *j*					Relationship bet CR *i* & TA *j*					Relationship bet CR *i* & TA *j*					Relationship bet CR *i* & TA *j*				
		Value	Satisfaction Level				Value	Satisfaction Level				Value	Satisfaction Level				Value	Satisfaction Level				Value	Satisfaction Level			
			Crisp	Fuzzy				Crisp	Fuzzy				Crisp	Fuzzy				Crisp	Fuzzy				Crisp	Fuzzy		
				(△1, △2)		S^*_{ijkt}			(△1, △2)		S^*_{ijkt}			(△1, △2)		S^*_{ijkt}			(△1, △2)		S^*_{ijkt}			(△1, △2)		S^*_{ijkt}
Thorough washing	0.313	0.3125					0					0.0625					0.3125					0.3125				
		90	0.65	0.01	0.34	0.73	45	0	0	0	0.00	30	0.8	0.1	0.19	0.82	95	1	0	0	1.00	0.5	0.8	0.27	0.17	0.78
		95	0.85	0.09	0.1	0.85	50	0	0	0	0.00	35	0.9	0.12	0.1	0.90	90	0.7	0.23	0.28	0.71	0.7	0.9	0.27	0.09	0.86
		98	1	0	0	1.00	60	0	0	0	0.00	40	1	0	0	1.00	80	0.4	0.02	0.07	0.41	1	1	0	0	1.00
Quiet Washing	0.25	0.3					0.5					0.1					0.1					0				
		90	1	0	0	1.00	45	1	0	0	1.00	30	1	0	0	1.00	95	0.85	0.09	0.14	0.86	0.5	0	0	0	0.00
		95	0.8	0.23	0.17	0.79	50	0.7	0.25	0.18	0.68	35	0.9	0.16	0.08	0.88	90	0.9	0.25	0.05	0.85	0.7	0	0	0	0.00
		98	0.7	0.13	0.27	0.74	60	0.4	0.07	0.48	0.50	40	0.6	0.19	0.29	0.63	80	1	0	0	1.00	1	0	0	0	0.00
Thorough rinsing	0.188	0.3					0					0.1					0.5					0.1				
		90	0.5	0.06	0.08	0.51	45	0	0	0	0.00	30	1	0	0	1.00	95	1	0	0	1.00	0.5	1	0	0	1.00
		95	0.9	0.07	0.09	0.91	50	0	0	0	0.00	35	0.6	0.19	0.2	0.60	90	0.8	0.08	0.14	0.82	0.7	0.9	0.08	0.09	0.90
		98	1	0	0	1.00	60	0	0	0	0.00	40	0.5	0.3	0.01	0.43	80	0.4	0.11	0.44	0.48	1	0.8	0.06	0.12	0.82
Less damage to clothes	0.125	0.231					0.077					0.077					0.231					0.384				
		90	1	0	0	1.00	45	1	0	0	1.00	30	1	0	0	1.00	95	1	0	0	1.00	0.5	1	0	0	1.00
		95	0.8	0.07	0.14	0.82	50	0.9	0.09	0.05	0.89	35	0.9	0.09	0.09	0.90	90	0.6	0.18	0.27	0.62	0.7	0.8	0.08	0.14	0.82
		98	0.7	0.09	0.06	0.69	60	0.9	0.09	0.07	0.90	40	0.8	0.09	0.19	0.83	80	0.5	0.33	0.48	0.54	1	0.5	0.12	0.25	0.53
Short washing time	0.125	0.714					0					0.143					0.143					0				
		90	0.7	0.23	0.29	0.72	45	0	0	0	0.00	30	1	0	0	1.00	95	0.6	0.26	0.31	0.61	0.5	0	0	0	0.00
		95	0.9	0.09	0.1	0.90	50	0	0	0	0.00	35	0.8	0.01	0.2	0.85	90	0.8	0.1	0.17	0.82	0.7	0	0	0	0.00
		98	1	0	0	1.00	60	0	0	0	0.00	40	0.6	0.01	0.39	0.70	80	1	0	0	1.00	1	0	0	0	0.00

<Table 2> The HoQ for Market Segment 2

	Weight	Washing Quality (%)					Noise Level (db)					Washing Time (min)					Rinsing Quality (%)					Clothes Damage Rate (%)				
		Relationship bet CR i & TA j					Relationship bet CR i & TA j					Relationship bet CR i & TA j					Relationship bet CR i & TA j					Relationship bet CR i & TA j				
		Value	Satisfaction Level				Value	Satisfaction Level				Value	Satisfaction Level				Value	Satisfaction Level				Value	Satisfaction Level			
			Crisp	Fuzzy				Crisp	Fuzzy				Crisp	Fuzzy				Crisp	Fuzzy				Crisp	Fuzzy		
				(△1,	△2)	S^*_{ijkt}			(△1,	△2)	S^*_{ijkt}			(△1,	△2)	S^*_{ijkt}			(△1,	△2)	S^*_{ijkt}			(△1,	△2)	S^*_{ijkt}
Thorough washing	0.3265	0.2875					0					0.1712					0.258					0.2833				
		92	0.7	0.12	0.15	0.71	54	0	0	0	0	39	1	0	0	1	81	0.7	0.06	0.18	0.73	1	1	0	0	1
		94	0.8	0.01	0.08	0.82	50	0	0	0	0	36	0.9	0.08	0.03	0.89	83	0.8	0.08	0.12	0.81	0.8	0.8	0.23	0.11	0.77
		96	1	0	0	1	46	0	0	0	0	33	0.8	0.07	0.15	0.82	85	1	0	0	1	0.6	0.6	0.59	0.03	0.46
Quiet Washing	0.0067	0					1					0					0					0				
		92	1	0	0	1	54	0.5	0.23	0.34	0.53	39	0	0	0	0	81	0	0	0	0	1	0	0	0	0
		94	0.85	0.27	0.11	0.81	50	0.7	0.12	0.19	0.72	36	0	0	0	0	83	0	0	0	0	0.8	0	0	0	0
		96	0.75	0.24	0.04	0.7	46	1	0	0	1	33	0	0	0	0	85	0	0	0	0	0.6	0	0	0	0
Thorough rinsing	0.2237	0.285					0					0.1828					0.2849					0.2738				
		92	0.6	0.27	0.31	0.61	54	0	0	0	0	39	1	0	0	1	81	0.5	0.11	0.16	0.51	1	0.8	0.25	0.13	0.77
		94	0.8	0.26	0.12	0.77	50	0	0	0	0	36	0.9	0.12	0.02	0.88	83	0.7	0.02	0.27	0.76	0.8	0.9	0.11	0.02	0.88
		96	1	0	0	1	46	0	0	0	0	33	0.8	0.07	0.17	0.83	85	1	0	0	1	0.6	1	0	0	1
Less damage to clothes	0.4156	0.2688					0					0.1495					0.2688					0.3129				
		92	1	0	0	1	54	0	0	0	0	39	0.6	0.19	0.23	0.61	81	0.5	0.38	0.4	0.51	1	0.5	0.29	0.1	0.45
		94	0.9	0.05	0.02	0.89	50	0	0	0	0	36	0.8	0.06	0.18	0.83	83	0.6	0.4	0.32	0.58	0.8	0.7	0.43	0.29	0.67
		96	0.7	0.21	0.27	0.72	46	0	0	0	0	33	1	0	0	1	85	1	0	0	1	0.6	1	0	0	1
Short washing time	0.0275	0.2152					0					0.3119					0.2654					0.2165				
		92	0.8	0.14	0.12	0.80	54	0	0	0	0	39	0.5	0.07	0.33	0.57	81	1	0	0	1	1	0.7	0.35	0.15	0.65
		94	0.9	0.02	0.07	0.91	50	0	0	0	0	36	0.7	0.15	0.29	0.74	83	0.8	0.08	0.18	0.83	0.8	0.8	0.05	0.07	0.81
		96	1	0	0	1	46	0	0	0	0	33	1	0	0	1	85	0.6	0.29	0.04	0.54	0.6	1	0	0	1

<Table 3> Cost and Customer Satisfaction Level for Market Segment 1

Washing Quality	Value (%)			90	95	98
	Cost	Crisp		3	4	5
		Fuzzy	c*	2.7425	3.9825	5.0575
			(△1, △2)	1.12, 0.09	0.12, 0.05	1.67, 1.9
	Accumulative Satisfaction	Crisp		0.1475	0.1716	0.1823
		Fuzzy		0.1530	0.1700	0.1820
Noise Level	Value (db)			45	50	60
	Cost	Crisp		5	3	2
		Fuzzy	c*	5.0625	3.0825	1.775
			(△1, △2)	1.67, 1.92	0.06, 0.39	0.91, 0.01
	Accumulative Satisfaction	Crisp		0.0769	0.0550	0.0335
		Fuzzy		0.07693	0.05365	0.04082
Washing Time	Value (min)			30	35	40
	Cost	Crisp		4	2	1
		Fuzzy	c*	4.07	2.23	1.2425
			(△1, △2)	0.81, 1.09	0.03,0.95	0.08, 1.05
	Accumulative Satisfaction	Crisp		0.0497	0.0425	0.0357
		Fuzzy		0.0499	0.0427	0.0363
Rinsing Quality	Value (%)			95	90	80
	Cost	Crisp		3	2	1
		Fuzzy	c*	2.6025	2.36	1.155
			(△1, △2)	1.59, 0	0.01, 1.45	0.33, 0.95
	Accumulative Satisfaction	Crisp		0.1444	0.1130	0.0766
		Fuzzy		0.1447	0.1144	0.0823
Clothes Damage Rate	Value (%)			0.5	0.7	1
	Cost	Crisp		4	2	1
		Fuzzy	c*	4.21	2.08	1.035
			(△1, △2)	0.14, 0.98	0.23, 0.55	0.03, 0.17
	Accumulative Satisfaction	Crisp		0.0829	0.0819	0.0782
		Fuzzy		0.0815	0.0800	0.0793

<Table 4> Cost and Customer Satisfaction Level for Market Segment 2

Washing Quality	Value (%)			92	94	96
	Cost	Crisp		3	4	5
		Fuzzy	c*	3.025	4.495	4.58
			(△1, △2)	0.56, 0.66	0.01, 1.99	1.69, 0.01
	Accumulative Satisfaction	Crisp		0.0945	0.0994	0.1036
		Fuzzy		0.0950	0.0988	0.1043
Noise Level	Value (db)			54	50	46
	Cost	Crisp		3	4	5
		Fuzzy	c*	2.84	3.585	5.26
			(△1, △2)	1.65, 1.01	1.77, 0.11	0.41, 1.45
	Accumulative Satisfaction	Crisp		0.0014	0.0020	0.0029
		Fuzzy		0.0015	0.0021	0.0029
Washing Time	Value (min)			39	36	33
	Cost	Crisp		1	2	3
		Fuzzy	c*	1.1225	1.9425	2.595
			(△1, △2)	0.03, 0.52	0.42, 0.19	1.65, 0.03
	Accumulative Satisfaction	Crisp		0.0593	0.0612	0.0635
		Fuzzy		0.0598	0.0614	0.0644
Rinsing Quality	Value (%)			81	83	85
	Cost	Crisp		1	2	4
		Fuzzy	c*	0.8475	1.835	3.7075
			(△1, △2)	0.67, 0.06	0.75, 0.09	1.23, 0.06
	Accumulative Satisfaction	Crisp		0.0660	0.0792	0.1132
		Fuzzy		0.0677	0.0804	0.1130
Clothes Damage Rate	Value (%)			1	0.8	0.6
	Cost	Crisp		1	2	3
		Fuzzy	c*	1.225	2.1775	2.645
			(△1, △2)	0.01, 0.91	0.01, 0.72	1.49, 0.07
	Accumulative Satisfaction	Crisp		0.0903	0.0964	0.1083
		Fuzzy		0.0867	0.0927	0.1027

From Problem (*P*) and Problem (*Q*), the optimal solutions of Problem (*P*) (crisp model) and Problem (*Q*) (fuzzy model) are obtained using MS Excel Solver as shown in <Table 5>. All the optimal solutions for these two problems are the same except four decision variables which are x_{221}, x_{231}, x_{112}, and x_{122}. In Problem (*P*), $x_{221}=1$, $x_{231}=0$, $x_{112}=1$, and $x_{122}=0$, while $x_{221}=0$, $x_{231}=1$, $x_{112}=0$, and $x_{122}=1$ in Problem (*Q*). Thus, it is showed in <Table 6> that the optimal solutions for the two problems mean that for both crisp model and fuzzy model, 95% is taken as level for washing quality, 40min for washing time, 95% for rinsing quality, and 1% for clothes damage rate in segment 1, and 54dB for noise level, 39min for washing time, 85% for rinsing quality, and 1% for clothes damage rate in segment 2, while noise level in segment 1 takes 50dB and 60dB for crisp and fuzzy model, respectively and washing quality in segment 2 takes 92% and 94% for crisp and fuzzy model, respectively.

Also, a comparison of the OCS obtained from the fuzzy model with that of the crisp case is given as follows:

$$\frac{0.8271-0.8436}{0.8436}\times 100=-1.9559\%.$$

The OCS obtained from the fuzzy model may be slightly worse or better than that in the crisp case, depending on what values the ranges for the customer satisfaction level and the cost for each alternative of TAs have. The advantage of using the fuzzy model is that ranges for customer satisfaction levels and cost value of TAs' alternatives are allowed in the problem.

<Table 5> The Optimal Solutions of Problem (P) and (Q)

	Problem (P)	Problem (Q)
x_{111}	0	0
x_{121}	1	1
x_{131}	0	0
x_{211}	0	0
x_{221}	1	0
x_{231}	0	1
x_{311}	0	0
x_{321}	0	0
x_{331}	1	1
x_{411}	1	1
x_{421}	0	0
x_{431}	0	0
x_{511}	0	0
x_{521}	0	0
x_{531}	1	1
x_{112}	1	0
x_{122}	0	1
x_{132}	0	0
x_{212}	1	1
x_{222}	0	0
x_{232}	0	0
x_{312}	1	1
x_{322}	0	0
x_{332}	0	0
x_{412}	0	0
x_{422}	0	0
x_{432}	1	1
x_{512}	1	1
x_{522}	0	0
x_{532}	0	0
OCS	0.8436	0.8271

4. Conclusions

This study deals with the more realistic situation in the QFD planning process where the values of TAs are taken as discrete as well as the ranges for customer satisfaction levels and cost value of TAs' alternatives are allowed since it is difficult to assign exact values to these data due to vague and/or imprecise information. In this research, the approach to deal with these imprecise data was proposed using some basic definitions of fuzzy sets and the signed distance method for ranking fuzzy numbers. By using the approach, the multiple choice 0-1 knapsack model for selecting a set of alternatives of TAs for each segment in a multi-segment market was extended to the fuzzy multiple choice 0-1 knapsack model.

In order to illustrate the proposed approach in this study, the QFD optimization problem for a washing machine with five CRs and five TAs under the two market segments including the fuzzy numbers was introduced. It was shown from this example that the difference between the optimal solution from the fuzzy model and that from the crisp model may occur depending on what the set of values the ranges for the customer satisfaction level and the cost of TAs' alternatives have, as well as the advantage of using the fuzzy model is that the imprecise data are allowed in the problem.

As future research in this area, more constraints such as technical difficulty, developing time and precedence relation for TAs' alternatives may be added to the model. Also, it should be interesting to incorporate a fuzzy theory into the model with the additional constraints.

<Table 6> Summarization of Results

Segments	Technical attributes	Crisp Model			Fuzzy Model		
		Alternatives	Customer satisfaction level	Cost	Alternatives	Customer satisfaction level	Cost
1	Washing quality (%)	95%	0.1716	4	95%	0.1700	3.9825
	Noise level (dB)	50dB	0.0550	3	60dB	0.0408	1.7750
	Washing time (min)	40min	0.0357	1	40min	0.0363	1.2425
	Rinsing quality (%)	95%	0.1444	3	95%	0.1447	2.6025
	Clothes damage rate (%)	1%	0.0782	1	1%	0.0793	1.0350
2	Washing quality (%)	92%	0.0945	3	94%	0.0950	3.0250
	Noise level (dB)	54dB	0.0014	3	54dB	0.0015	2.8400
	Washing time (min)	39min	0.0593	1	39min	0.0598	1.1225
	Rinsing quality (%)	85%	0.1132	4	85%	0.1130	3.7075
	Clothes damage rate (%)	1%	0.0903	1	1%	0.0867	1.2250
OCS		0.8436			0.8271		

Acknowledgements

This work was supported by the Dong-A University research fund.

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