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Fuzzy group decision-making for multi-format and multi-granularity linguistic judgments in quality function deployment

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ABSTRACT

As a customer-driven tool, quality function deployment (QFD) is widely used in product planning or improvement to achieve higher product performance and customer satisfaction. QFD uses a matrix called the house of quality (HoQ) to translate customer requirements (CRs) into engineering characteristics (ECs). Constructing the HoQ, which includes determining the importance weights of CRs, the correlation matrix among ECs and the relationship matrix between CRs and ECs, is an important issue in the application of QFD. However, decision-makers (DMs) participating the construction of HoQ tend to give their individual judgments in multi-format or multi-granularity depending on their different knowledge, experience, culture and circumstance. Furthermore, these judgments are more difficult to assess with the precise quantitative forms due to the vagueness and uncertainty existed in the early stage of new product development. In this paper, a group decision-making approach incorporating with two optimization models (i.e. logarithmic least squares model and weighted least squares model) is proposed to aggregate these multi-format and multi-granularity linguistic judgments. Fuzzy set theory is utilized to address the uncertainty in the decision-making process. The proposed method is illustrated with a real-world case of horizontal directional drilling machine. The application indicates that the group decision-making method may be a promising tool for constructing the HoQ.

1. Introduction

New product development is a crucial source of new sales and profits for enterprises under the environment of global competition. Shorter lead time, lower product cost, and higher customer satisfaction and market share which are the emphases of competition enable Quality Function Deployment (QFD) to be an important tool for new product development (Büyüközkan & Feyzioglu, 2004; Fung, Tang, Tu, & Wang, 2002; Kwong & Bai, 2002; Maffin & Braiden, 2001). QFD, as a well-known product planning approach, supports engineers to translate the "voice of customer", i.e. customer requirement (CRs), into engineering characteristics (ECs), and subsequently into parts characteristics (PCs), process plans and production requirements through various stages in new product development (Hauser & Clausing, 1988; Griffin & Hauser, 1993). Each translation can be represented graphically in a matrix configuration generally known as the house of quality (HoQ) (Karsak, 2004).

The first translation, called HoQ of product planning, will be focused on analyzing in this paper since it can largely affect the target value setting of other translations in the later design stages. The crucial and essential activity in the application of QFD is to construct the HoQ accurately, which includes determining the importance weights of CRs, the relationship matrix between CRs and ECs, and the correlation matrix among ECs. As it is not the focus of this study, the authors do not discuss how to derive the importance weights of ECs which is another critical problem for the calculation of HoQ. Various methods have been developed to tackle with the construction of HoQ. The simplest method in prioritizing CRs is based on direct-rating scale, such as nine-point (Griffin & Hauser, 1993). Gustafsson and Gustafsson (1994) employed a conjoint analysis method in the form of pairwise comparisons to determine the relative importance of CRs. Analytic hierarchy process (AHP), a multi-criteria decision-making approach, was also used in weighting the importance of CRs under different circumstances (Akao, 1990; Armacost, Componation, Mullens, & Swart, 1994; Lu, Madu, Kuei, & Winokur, 1994). Considering the issue as a typical group decision-making problem, Lai, Ho, and Chang (1998) applied in the decision-making process combining voting and linear programming techniques to aggregate individual preference into group consensus. Ho, Lai, and Chang (1999) also proposed an integrated group decision-making method to aggregate team members' opinions and minimize inconsistency over group and individual preferences for determining the importance weights of CRs. However, these aforementioned methods cannot

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effectively capture the inevitable vagueness and uncertainty in the decision-making process. Chan, Kao, Ng, and Wu (1999) combined fuzzy arithmetic and entropy method to calculate the importance weights based on converting the importance assessment from crisp values to fuzzy numbers. Büyüközkan, Feyzioglu, and Ruan (2007) and Kwong and Bai (2002, 2003) employed group decision-making method and AHP incorporated with fuzzy set theory to determine the importance weights of CRs, respectively. By using fuzzy mathematical programming, Lai, Xie, Tan, and Yang (2008) rated CRs from three aspects, i.e. competition position, current performance and customers' viewpoint. To reason about the implicit relationships between CRs and ECs and the correlations among ECs, Temponi, Yen, and Tiao (1999) developed a heuristic inference scheme based on a fuzzy logic-based extension to HoQ and a formal representation of requirements. Based on the quantified representation of ECs and customer perceptions, fuzzy regression approaches were developed to identify the relationship matrix between CRs and ECs (Kim, Moskowitz, Dhingra, & Evans, 2000; Fung, Chen, & Tang, 2006).

As a typical group decision-making process, decision-makers (DMs), who may be product designers and managers, generally give their own judgments to construct the HoQ in many different ways, numerically or linguistically, depending on their individual culture, experience, knowledge and circumstance. However, determining consensus group decisions is not an easy task under so complex circumstances. Thus, Büyüközkan et al. (2007) proposed a fuzzy group decision-making approach to fuse multiple preference styles to respond CRs. Customers were assumed to give their importance values according to the following five formats, i.e. preference orderings, utility analysis, optimal subset method, linguistic preference relations and fuzzy pairwise comparisons. These five formats were unified by using corresponding transformation functions or LOWA operator (Chiclana, Herrera, & Herrera-Viedma, 1998; Yager, 1996). Note that DMs participating the construction of HoQ should have good insights of CRs, ECs and other issues with regard to the developing product. Preference orderings and optimal subset method may be effective for customers to express their opinions but not for DMs because they can not provide adequate information to well express the opinions. For example, DMs can not compare the degrees of priorities among CRs through these two methods. Furthermore, for requiring the expected performance of each criteria to be represented with a quantitative form, utility analysis is also not appropriate to be used at the early design stage in which some design criteria are hard to be quantified precisely (Thurston & Carnahan, 1992; Wang, 2001). From various studies mentioned in this paper, linguistic preference relations and fuzzy pairwise comparisons can be found as the familiar formats for DMs to give their assessments in constructing the HoQ. Considering their personal backgrounds and different understanding levels to the developing product, DMs may use different linguistic term sets to express their own judgment information (Herrera, Herrera-Viedma, & Martínez, 2000). To determine the relative weights in fuzzy comparison matrix, the general method was to solve crisp matrix obtained from the fuzzy matrix based on the indices of confidence and optimism provided by the participators (Kwong & Bai, 2002). For the purpose of handling the multi-granularity linguistic information in linguistic preference relations, most methods were generally adopted transformation functions to unify the information into a uniform representation base (Chiclana et al., 1998, Herrera et al., 2000). However, the two aspects mentioned above, i.e. determining the indices of confidence and optimism and unifying the multi-granularity linguistic information by using a transformation function, increase the DMs' subjectivity distinctly and then lead to higher uncertainty in the decision-making process. To decrease the subjectivity and reach a better group consensus, a fuzzy group decision-making approach incorporated with two optimization models (logarithmic least squares model and weighted least squares model) is proposed to aggregate these assessments for constructing the HoQ.

The rest of the paper is arranged as follows. Section 2 presents the problem for constructing the HoQ in linguistic preference relations and fuzzy pairwise comparisons with seven granularities. In Section 3, a new approach integrating the LLSM and WLSM is proposed to obtain the aggregated judgments. In Section 4, an application in a real-world product development of horizontal directional drilling (HDD) machine is used to illustrate the proposed method. Section 5 concludes the paper.

2. Presentation of the problem

The construction of HoQ consists of determining the importance weights of CRs, the relationship matrix between CRs and ECs, and the correlation matrix among ECs. Considering the comparability of the decision-making process for the three aspects mentioned above, the determination of importance weights of CRs is provided to describe in detail.

Let $R = (r_1, r_2, \ldots, r_n)$ be the set of CRs for the HoQ of product planning.

Assume there are m DMs associated with a weight vector $V = (v_1, v_2, \ldots, v_m)$, where $0 \leqslant v_i \leqslant 1$ and $\sum_{i=1}^{m} v_i = 1$. Bodily (1979) developed a straightforward approach which collects voting weights for each DM by a delegation subcommittee made up of other DMs to derive each DM weight. Here, the Bodily' method is utilized to obtain the weights of DMs ("0–1" express from "no important" to "very important").

The DMs can give their judgments according to the following two formats:

- Fuzzy pairwise comparisons. DMs can provide their priorities among n CRs in a fuzzy pairwise comparison matrix as follows

$$\widetilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix}, \quad \text{where} \quad \tilde{a}_{ij} = 1/\tilde{a}_{ji} \quad \text{and} \quad a_{ii} = 1.$$

- Linguistic preference relations. DMs can express their opinions on n CRs by using a linguistic preference vector $U = (u_1, u_2, \ldots, u_n)$, where u_i is the linguistic preference of the ith requirement.

The general linguistic term sets consist of the following nine terms, i.e. very low (VL), very low to low (VLL), low (L), medium low (ML), medium (M), medium high (MH), high (H), high to very high (HVH), and very high (VH). The multi-granularity linguistic term sets, $S^1, S^2, \ldots, S^c$, which can be quantified through triangular fuzzy numbers $\tilde{a}_i = (a_{il}, a_{ig}, a_{iu})$ or trapezoidal fuzzy numbers $\tilde{a}_i = (a_{il}, a_{ig}, a_{ih}, a_{iu})$, are given as follows. For the fuzzy pairwise comparison format, three linguistic term sets between $\tilde{1}$ to $\tilde{9}$ are given as follows (Kwong & Bai, 2002; Chan, Kumar, Tiwari, Lau, & Choy, in press)

S^1	FNs	S^2	FNs	S^3	FNs
$s_1^1 - VL$	$(1,1,2)$	$s_1^2 - VL$	$(1,1,3)$	$s_1^3 - VL$	$(1,1,1.5)$
$s_2^1 - VLL$	$(1,2,3)$	$s_2^2 - L$	$(1,3,5)$	$s_2^3 - VLL$	$(1.5,2,2.5)$
$s_3^1 - L$	$(2,3,4)$	$s_3^2 - M$	$(3,5,7)$	$s_3^3 - L$	$(2.5,3,3.5)$
$s_4^1 - ML$	$(3,4,5)$	$s_4^2 - H$	$(5,7,9)$	$s_4^3 - ML$	$(3.5,4,4.5)$
$s_5^1 - M$	$(4,5,6)$	$s_5^2 - VH$	$(7,9,9)$	$s_5^3 - M$	$(4.5,5,5.5)$
$s_6^1 - MH$	$(5,6,7)$			$s_6^3 - MH$	$(5.5,6,6.5)$
$s_7^1 - H$	$(6,7,8)$			$s_7^3 - H$	$(6.5,7,7.5)$
$s_8^1 - HVH$	$(7,8,9)$			$s_8^3 - HVH$	$(7.5,8,8.5)$
$s_9^1 - VH$	$(8,9,9)$			$s_9^3 - VH$	$(8.5,9,9)$