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Towards a QFD-based expert system: A novel extension to fuzzy QFD methodology using rough set theory

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ABSTRACT

Quality function deployment (QFD) has been widely recognized as an effective means to develop quality products that can maximize customer satisfactions. This paper presents a novel extension to the fuzzy QFD methodology using rough set theory, with the aim to facilitate decision making in the early stages of product development and lead to the establishment of a QFD-based expert system for product design. The proposed rough-fuzzy QFD system combines fuzzy arithmetic operations with the two novel concepts of rough number and rough boundary interval that are derived from rough set theory. A comparison between the proposed methodology and the traditional fuzzy QFD was performed. It has been shown that the proposed methodology not only can provide more insights into the vague voices of customers and technologists, but also can suppress the enlargement of boundary intervals after each arithmetic operation in QFD analysis. This would help in improving the discernibility of design objectives and thus facilitate the decision making in product development.

1. Introduction

The success of manufacturing firms depends on their ability to understand the needs of customers and develop customer-oriented products at low production cost. Thus, it is necessary to pay special attention to customer needs (CNs) analysis in product development besides considering the technical capabilities of a manufacturing firm. In general, product development is a complex process involving intensive information processing and decision making activities. Accordingly, it is always a crucial task to understand the true needs of customers and then apply decision making techniques to efficiently and effectively transform these needs into new products and services at reduced cost and shorter time to market. However, customers speak a different language from designers. Hence, understanding the voice of customers (VOCs) is more difficult than it appears. In this respect, quality function deployment (QFD) which was originated in Japan in the 1970s provides a widely used product development methodology for understanding customer needs and product fulfilment (Shillito, 1994). In QFD, the process of product development involves all members from customers to designers, through inter-functional planning and communication.

In QFD, the desires of customers about a product are taken into account through survey. These desires are treated as a set of customer needs (CNs). A number of technical requirements (TRs) that affect CNs are also identified by domain experts in order to maximize customer satisfactions. QFD facilitates decision making in product development management by prioritizing CNs and TRs through a process called house of quality (HOQ), which relates CNs (known as 'WHATs' in QFD) to TRs (known as 'HOWs' in QFD) using a chart (Hauser & Clausing, 1988). However, QFD analysis can be a complicated decision making process as it involves the understanding of vague and subjective perceptions solicited from both customers and technologists (Kim & Kim, 2009). In this respect, fuzzy logic-based approach to QFD has received the most attention due to its ability in representing and analyzing the inherent fuzziness of the design information. Basically, QFD contains subjective and vague linguistic statements such as 'low importance', 'high importance', 'strong relationship', and 'weak relationship'. Frequently, such linguistic terms are represented by fuzzy numbers, which can be manipulated by the mathematical operations provided by fuzzy set theory (Chen & Weng, 2003; Khoo & Ho, 1996; Temponi, Yen, & Tiao, 1999). For instance, Khoo and Ho (1996) used symmetrical triangular fuzzy numbers (STFNs) to perform QFD analysis. Chan and Wu (2005) employed STFNs to analyse and prioritize customer needs as well as product design requirements. Fuzzy approaches based on fuzzy arithmetic, and/or fuzzy defuzzification (Shen, Tan, & Xie, 2001; Vanegas & Labib, 2001; Wang, 1999; Zhang & Chu, 2009) had also been developed to deal with imprecise and vague descriptions of customer needs.

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Other than the traditional fuzzy QFD method, some interesting attempts using analytic hierarchy process (AHP), rough sets and Kano's model have also been proposed to quantify and analyse the importance ratings of customer needs in QFD (Armacost, Componation, Mullens, & Swart, 1994; Li, Tang, Luo, & Xu, 2009).

However, further investigation shows that the traditional representation and processing of vague and imprecise information in QFD may be subjective, complex or controversial. For example, the widely used fuzzy number based QFD analysis has some critical drawbacks. First of all, the membership function of fuzzy number is difficult to define. Frequently, it is predetermined by experts subjectively, which may not be in good agreement with actual facts. Second, the boundary intervals of fuzzy numbers expand rapidly as a result of fuzzy arithmetic operations. More specifically, it has been observed that after each arithmetic operation between two fuzzy numbers, the boundary interval of the resultant fuzzy number tends to become larger. The enlargement of boundary intervals after fuzzy arithmetic operations may lead to low discernibility of the resultant fuzzy numbers, affect the prioritization of customer needs and technical requirements, and ultimately influence the decision making in product development management.

This work examines the inherent vagueness in expressing the voice of customers as well as the voice of technologists, and proposes a rough-fuzzy QFD methodology based on the two novel concepts of rough number and rough boundary interval, to address the above issues. It aims to improve the effectiveness and efficiency in prioritizing customer needs and technical requirements, so as to facilitate the decision making in product development management. The paper is organised as follows. Section 2 reviews the basic concepts of fuzzy membership function and fuzzy number, as well as the fundamental notions of rough set theory. Two novel concepts, rough number and rough boundary interval are derived from the basic principles of rough sets. Section 3 proposes a hybrid rough-fuzzy QFD methodology that combines the two novel concepts with fuzzy arithmetic operations. A comparative study is presented in Section 4. It illustrates the advantages of the new methodology in handling the vague design information as well as in improving the effectiveness and efficiency for the prioritization of customer needs and technical requirements. Finally, the major conclusions achieved in this work are summarized in Section 5.

2. Fuzzy number and rough number

2.1. Fuzzy number and fuzzy arithmetic operations

Since its inception, fuzzy set theory in which sets without clear boundaries are defined by partial membership instead of crisp membership used in classical definition of a set has been widely used to deal with uncertainty and vagueness, in QFD for example. More specifically, in fuzzy set theory, an element can belong to a set to a degree k ($0 < k < 1$), in contrast to classical set theory where an element must definitely belong or not to a set. However, the issue pertaining to how to define the value of k has invited much discussion, and frequently, a so-called membership function that is obtained based on subjective judgment is used to provide the value. For instance, the linguistic terms contained in QFD can be represented using triangular fuzzy numbers (TFNs). These TFNs are denoted by (C, L, U), where L and U are the lower and upper boundaries of the fuzzy number and C is the value corresponding to the maximum grade of membership. The addition or subtraction operation between two TFNs would yield a TFN. As for multiplication or division operation, strictly speaking, it will not result in a TFN. However, for simplicity, it is often treated as a TFN as an approximation.

Mathematically, if $TFN_1 = [L_1, U_1]$ and $TFN_2 = [L_2, U_2]$ are two fuzzy numbers, where L_1 and L_2 are their lower boundaries, and U_1 and U_2 are their upper boundaries, respectively, then

$$TFN_1 + TFN_2 = [L_1, U_1] + [L_2, U_2] = [L_1 + L_2, U_1 + U_2], \quad (1)$$

$$TFN_1 \times k = [L_1, U_1] \times k = [kL_1, kU_1],$$
$$TFN_2 \times k = [L_2, U_2] \times k = [kL_2, kU_2], \quad (2)$$

where k is a constant, and

$$TFN_1 \times TFN_2 = [L_1, U_1] \times [L_2, U_2] = [L_1 \times L_2, U_1 \times U_2]. \quad (3)$$

2.2. Rough set theory

Rough set theory, which was proposed by Pawlak (1982) in the 1980s, expresses vagueness by means of the boundary region of a set instead of using membership function. If the boundary region of a set is empty, the set is crisp. Otherwise, the set is rough (or inexact). Non-empty boundary region of a set implies that the knowledge about the set is not sufficient to define it precisely. Although sometimes treated as the complement of fuzzy set theory, rough set theory has its own advantages in dealing with vagueness and uncertainty (Zhai, Khoo, & Zhong, 2007). The unique merit of rough sets is its collective analysis of imprecise data without the need for any preliminary or additional information. Rough sets remains the objectivity of the given data and do not require any subjective adjustment when processing the data.

In general, the notion of rough sets can be explained using topological operations, interior and closure, known as approximations. Rough sets provide a set of mathematical means to describe the vagueness of data through approximations. In rough set theory, any vague or uncertain concept (sometimes known as 'class' in classification) can be represented by its lower approximation and upper approximation. The former comprises a set of elements that can be certainly classified within a concept (class) based on available information, whereas the latter consists of a set of elements that can possibly be classified within a concept (class) based on available information. The boundary region of such a concept or class is a set of elements that can be classified neither within a concept (class) nor its complement. Fig. 1 shows the basic notion of approximations in rough sets.

2.3. Rough number and rough boundary interval

Instead of using pre-defined fuzzy membership functions based on subjective assumptions, imprecise descriptions of customer needs and technologist evaluations can be quantified via collective analysis using rough set theory. As mentioned earlier, one of the characteristics of rough set theory is that its parameters are determined directly from the given data and no auxiliary information is needed (Pawlak, 1991). As a result, in rough set theory, the degree of imprecision is not pre-assumed as it is done in probability theory or fuzzy set theory. More specifically, it is described by the aforementioned concept of approximations (Khoo & Zhai, 2001).

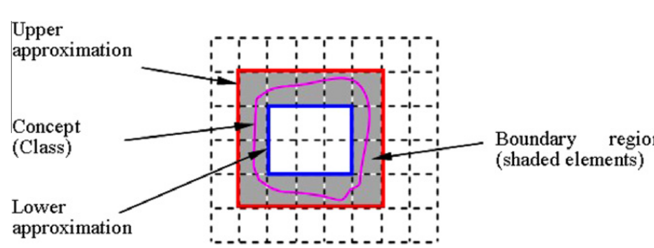

Fig. 1. Approximations in rough sets.