Two uncertain chance-constrained programming models to setting target levels of design attributes in quality function deployment

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\section{A B S T R A C T}

Quality function deployment (QFD) is widely acknowledged as a customer-oriented product design tool, which is generated by translating consumer demands into design attributes of a product. In order to depict the internal ambiguous factors in the development process more appropriately, uncertain variables with a specialized kind of regular uncertainty distributions based on uncertainty theory are applied. Subsequently, two uncertain chance-constrained programming (CCP) models used for formulating the QFD procedure are set forth, whose objectives are maximizing the consumer satisfaction and minimizing the design cost, respectively. To demonstrate the feasibility of the proposed modelling approach, an example of the motorcycle design problem is illustrated, in which the new target levels of design attributes are selected and analyzed according to the decision-makers' subjectivity and preference at different confidence levels. Additionally, a comparative study between the uncertain CCP approach and another uncertain expected value modelling approach is conducted. The results indicate that uncertain CCP models are more suitable for optimization in the QFD procedure.

\section{1. Introduction}

Nowadays, the burgeoning demands of diversified and personalized products have pushed manufacturing industries to chase consumers’ continuous and changeable needs in a faster pace. Therefore, dynamic and fierce competition emerges from the global market. To break this situation, many companies have adopted various product development tools to seek for permanent competence in seizing benefits. Quality function deployment (QFD) is a popular one among these tools, which can be traced back to the late 1960s \cite{1}. It is a comprehensive method devoting to interpreting consumer demands (CDs) into design attributes (DAs) of the target product and ensuring the improved product to gain more customer support.

The house of quality (HoQ) is the core concept of QFD, which consists of several matrices based on “whats (CDs) - hows (DAs)” \cite{11}. CDs and their relative importance weights are summarized on the left wall of an HoQ. The ceiling reflects each DA and the roof signifies correlations among DAs. And the body reveals relationships between CDs and DAs. In addition,
the ground is furnished with the observed data of target levels for DAs, which is denoted by the quantitative technical specifications of DAs required to satisfy each CD.

As to a new or improved product, the QFD procedure aims at determining a series of target levels for DAs under resource constraints, whose overall consumer satisfaction is supposed to be equal to or larger than that of any other potential competitors in the market. In real-life applications, definitely multiple variables, trade-offs and contradictions will be involved. To deal with this complex operation course, an increasing number of programming models with different objectives have been arisen. Before establishing the optimization model, it is significant to confirm the relative importance weights of CDs and the internal relations and correlations in the HoQ. In the former literature, generally these elements were determined to be crisp, stochastic or fuzzy variables in a subjective way \[7,12,27\], or objectively determined from fuzzy linear regressions \[3,4,19\] or non-linear regressions \[20\].

As a crucial branch of the QFD research, abundant fuzzy modelling studies regarding how to get a series of target levels for DAs have been carried out. It seems quite reasonable to absorb fuzziness to express the inner indeterminate factors in HoQ with the aid of the fuzzy set theory. For example, Chen et al. \[5\] brought up a fuzzy expected value model to determine DAs' target levels, which was separately in consideration of the maximum consumer satisfaction or the minimum development expense. Erginel \[9\] set forth a fuzzy multi-objective decision model which contains the information from design failure and effect analysis. The means-end chain notion was incorporated by Chen and Ko \[4\] to establish a fuzzy linear modelling approach in calculating the contribution of individual “how” to the whole consumer satisfaction. Sener and Karsak \[24,25\] suggested some fuzzy mathematical programming models to determine target levels of DAs, including a fuzzy non-linear regression and optimization method, and an approach of combining a fuzzy linear regression and a fuzzy multiple objective programming. Liu et al. \[20\] embedded the compensation degree among CDs into QFD, which was realized by integrating the minimum fuzziness benchmark into a non-linear regression. A fuzzy least-square regression approach to depicting relationships in QFD was considered by Kwong et al. \[14\], which took both the fuzziness and randomness into account. Zhong et al. \[29\] set up a fuzzy chance-constrained programming in determining target levels of DAs, which was solved by a hybrid intelligent algorithm. Recently, Liu et al. \[17\] proposed an exact expected value-based method to prioritize DAs in fuzzy QFD, in which the expected values of the importance weights of DAs were obtained through the inverse credibility distribution of fuzzy numbers.

It is observed that the parameters involved in the QFD procedure are usually set as crisp or fuzzy values. Nevertheless, it is not very appropriate since either the probability theory or the fuzzy set theory may lead to counterintuitive outcomes under some circumstances \[16\]. Consequently, some researches based on uncertainty theory \[16\] were accomplished to mend this defect, such as uncertain finance \[23\], uncertain risk aversion \[30\], uncertain risk and reliability analysis \[15\], and uncertain minimum spanning tree problems \[31\], etc. Besides, uncertain chance-constrained programming (CCP) model was employed in project scheduling problems \[13\] and job shop scheduling problems \[26\] or other practical applications. With respect to the application of uncertainty theory to QFD, relevant studies are very limited. Liu et al. \[18\] utilized an uncertain expected value-based method to determine the importance weights of DAs. On this basis, Yang et al. \[28\] generalized it to the strategic management of logistics services in prioritizing several strategic actions. Miao et al. \[21\] proposed an uncertain value modelling (EVM) approach to setting target levels of DAs. It can be seen that uncertainty theory has gained extensive support and acknowledgement from other fields as mentioned, but it has not been widely applied to QFD yet.

Therefore, a novel approach based on uncertainty theory and uncertain chance-constrained programming is put forward to formulate the QFD procedure in this paper. Analogous to fuzzy optimization, relative importance weights of CDs, relations between CDs and DAs, correlations among DAs, along with the variable fulfillment charge for each unit of DA, are pre-determined as uncertain variables by experts. To vividly and specifically describe these vague information, uncertain variables with a certain kind of regular uncertainty distributions is applied. Afterwards, two uncertain chance-constrained programming models with two different considerations are proposed to determine target levels of DAs in actual manufacturing. For the sake of enhancing the company's competitiveness, the goal of the first model is to maximize the overall consumer satisfaction. In consideration of the company's current financial condition, the goal of the second model is to minimize the total design cost. It is noted that fuzzy CCP models are usually difficult to solve in many applications, whose results are usually obtained with the help of simulations and heuristic algorithms \[8,29\]. However, we transform our models analytically into equivalent deterministic models through inverse uncertainty distributions and solve them by MATLAB, which largely simplifies the calculation procedure.

The rest of the article is arranged as follows. In regards to the imprecise factors in the QFD procedure, two uncertain CCP models in setting target levels of DAs are set forth in Section 2. Furthermore, Section 3 demonstrates a case study on a motorcycle design problem to address the effectiveness of the proposed method. And a comparison between uncertain CCP and EVM is also generated. Finally, some important conclusions and our major contributions are elaborated in Section 4.

2. Uncertain chance-constrained programming in QFD

In the process of setting target levels of DAs, some indeterminate elements are involved, like relative importance weights of CDs, relationships between CDs and DAs and correlations among DAs. These ambiguous factors are usually assumed to be random variables, whose probability distributions are mostly obtained via statistical estimation. Practically, due to the lack of comprehensive information, the evaluated probability distribution may significantly disagree with the accumulative
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