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ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 12 (23): 7222-7227, 2013
ISSN 1812-5638 / DOI: 10.3923/itj.2013.7222.7227

Mechanical Design Requirements Analysis Based on DQFD

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Abstract: The change of mechanical design requirements is throughout the whole life cycle, if not handled timely and effective, will affect the component quality and mechanical product development speed. Firstly, the traditional quality function deployment is extended to Dynamic Quality Function Deployment (DQFD) in order to adapt to the changing requirements, meanwhile the author builds three-dimensional house of quality as its core tool. According to the vagueness and uncertainty of customer requirements, the author provides the systematic analytical framework of mechanical design requirements based on DQFD combining with grey system theory especially GM (1, N) and calculate the importance of requirements and the relationship between requirement and technology by means of grey relational algorithm and then converted to sequence of technical characteristics importance. Through the application in the design and development of mechanical product in the future, it will be proved to reduce the cost of information collection and improve the accuracy of information processing and improve the quality and credibility of mechanical product and component.

Key words: Dynamic quality function deployment, GM (1, N), mechanical design, requirement analysis

INTRODUCTION

As is known to all, in order to adapt to market competition and provide high-quality products or service, it's foremost to know about customers, understand their needs and develop product in a customer-oriented way. It's a common objective for most mechanical product development teams to deploy high-quality component and product, which can satisfy customers' real needs on time and on budget. Customer Requirements (CRs) of mechanical product are diverse and dynamic. The dynamic changes of CRs mainly include that gradually generated in a period of time and that taken place at a certain point of time. It is the changes that extend to the downstream of product development, thus influencing the product development design and quality assurance. The uncertainty of mechanical design requirements exists in the whole process of the product's life cycle (Westfall, 2005), which if not dealt with timely and effectively, would impact the component quality and development progress and further violate the trust relationship between developers and users (Liu and Guo, 2002). Therefore, it is a big issue in design engineering especially in mechanical engineering field, to solve the needs-changing problem effectively during the product development process.

Quality Function Deployment (QFD) properly and effectively transfers customer requirements' information into product technical target and operation control regulations, thus matching the design and product with customers' needs (Akao, 1996), providing a systemic method that ensures the product quality and applicability in all dimensions since the initial stage of development. QFD theory has certain help to analyze, transfer mechanical design requirements and to improve product quality, which was proven by massive literatures about the application of QFD in product development (Tran and Sherif, 1995; Liu, 2000; Haag *et al*., 1996). However, due to the structural restriction of the two-dimensional house of quality (2D-HOQ), traditional QFD can only map the static users' needs, which lacks of analyses and planning of the corresponding to the need changes. Therefore, to realize the analyses and transmission of the dynamic needs, dynamic quality function deployment theory (DQFD) and three-dimensional house of quality (3D-HOQ) technology and grey forecasting model aiming at dynamic needs, are put forward by scholars (Xiong and Ding, 2008; Wang and Xiong, 2010; Wang, 2010). But, these theories are used separately, not forming a systemic analysis framework, which implicates that the research angle has the potential to be expanded.

This study tries to apply GST within the DQFD, to build a systemic analysis framework for digging design

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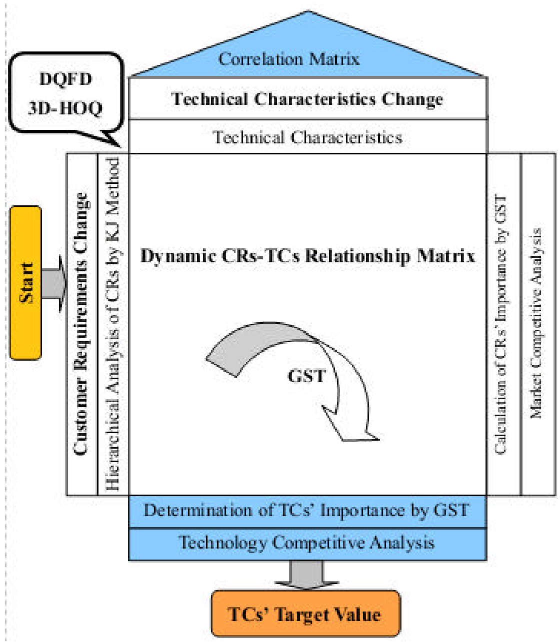

Fig. 1. Conceptual model of requirement transformation

requirements, thus realizing an accurate analysis and transmission of dynamic requirements, improving product quality and accelerating development progress. Besides, this systemic theory is applied to a certain product development project to give a deeper explanation and analysis.

REQUIREMENT ANALYSIS OF MECHANICAL DESIGN

Based on the extant research (Xiong and Ding, 2008; Wang and Xiong, 2010; Wang, 2010; Li, 2010; Wei *et al.*, 2005), DQFD method which is of expansion is put forward here. Being based on the traditional 2D-HOQ, the dimensionality of change is added on the basis of the dimensionality of customer requirements and Technical Characteristics (TC) and expand it a 3D-HOQ as the core tool of realizing the conversion of dynamic demand. Meanwhile, the dynamic design requirements are effectively converted into the TC and unfold it one layer on order and mapped to product development in the process of design using GST to influence changes of CR and the concept model as shown in Fig. 1.

The ways of market research, scene analysis and expert interview are used to get the CRs and discuss them one by one, imagine scene example and analyzes the requirement and psychology by means of 5W1H (Who, Why, When, What, Where, How) in order to form more comprehensive understanding of CRs. Then, sort and cluster the language information with KJ method (affinity chart) and probe into the requirement project, take the project needed next successively and construct the requirement table according to the different categories such as function, performance and quality requirements, etc. Next, to discuss the changes that maybe happen during the whole development cycle, analyze the trend of change, adjust the results of analysis and form the table of dynamic demand. And then, do the analysis according to the following steps (Li, 2010; Wei *et al.*, 2005; Liu *et al.*, 2010).

Calculate importance degree of dynamic CRs

Construction of CRs' survey matrix: Let the customers or the experts grade the requirement satisfaction on the basis of experience and power with the levels from very satisfied to very unsatisfied and score from 1 to 9. Suppose that there are s customers or experts grade m pieces of requirement satisfaction, then get the matrix of CRs.

Calculation of CRs' relative importance: Firstly, handle the evaluation matrix of CR importance by dimensionless and ruled out of the inconsistent index that would affect the result. There are different methods to deal with different situations when handle multiple indexes by dimensionless and relevant documents and researches can be referred to. That is omitted here, for it is not the focus of this research.

Secondly, calculate the absolute D-value and the maximum and the minimum difference of CR vector and original vector of both ends at each point:

$$\Delta_i(j) = \left| x_i^{'}(k) - x_i(k) \right|$$

$$\Delta_{max} = \max_i \max_s \Delta_i(k), \Delta_{min} = \min_i \min_s \Delta_i(k)$$

Again, using grey correlation analysis, solve the grey relational coefficient of the transformed requirement vector sequence to the original vector at the point of:

$$k : \varepsilon(j) = \frac{\Delta_{min} + \rho \cdot \Delta_{max}}{\Delta_i(s) + \rho \cdot \Delta_{max}}$$

In which, ρ is the given resolution coefficients which is used to weaken the distortion to improve the obvious difference among the correlation coefficients and $\rho \in (0, 1)$. At last, calculate the grey correlation of transformed sequence of CRs to the original sequence and solve the relative importance of CRs. That is:

$$e_i = \frac{1}{s}\sum_{k=1}^{s}\theta_j \varepsilon(j), \sum_{k=1}^{s}\theta_j = 1$$

Grey correlation of competitive requirement matrix: Same as above, grade the competitive requirement according to the actual situation by means of customer survey, information collection of competitors and interviews and other methods in order to construct m matrixes of competitor's CR.Then, same with the method of calculating grey correlation. First, to dimensionless the value of the original competition

For the second step, calculate the absolute D-value and the biggest and the minimum difference of CR vector and original vector at each point. Take $X_0 = \{x_0(j), j = 1, 2, \cdots, k\}$ as the benchmark vector sequence and X_0 includes k1.

Again, using grey correlation analysis, solve the grey relational coefficient of the transformed requirement vector sequence to the original vector at the point of:

$$k : \varepsilon(j) = \frac{\Delta_{min} + \rho \cdot \Delta_{max}}{\Delta_i(m) + \rho \cdot \Delta_{max}}$$

At last, calculate the grey correlation of transformed sequence of CR to the original sequence, which namely the importance of competitive factors, ω_i.

Determination of CRs' importance degree: According to the relative importance of CR from above two steps e_i and the competitive factors importance ω_i, solve the CR importance:

$$p_i = e_i \times \omega_i, i = 1, 2, \cdots, m$$

Fix correlativity of dynamic Crs-TCs

Construct Evaluation Matrix of Technology Competitiveness: The evaluation of technology competitiveness is the evaluations of internal staff to the technical level. The method of construction is similar to the competitive requirement matrix, which is illustrated in 1.1.2 and omitted here.

Determine correlativity by grey relativity:

- Build grey correlation sets based on the original competitive matrix of CR and the matrix of technology competitiveness

Build factor set $X = \{x_0, x_1, \cdots, x_n\}$, x_0 is the first CRs as the reference sequence and $x_1, x_2, \cdots, x_n$ are n TCs as the comparative sequence. And x_0 (k) is the satisfactory of the rival company which number is k to the first CR; x_i (k) is the index value of its TC.

- Normalize the original data, using the same method of dimensionless as mentioned above
- Calculate the absolute D-value and the biggest and the minimum difference of CR vector and original vector at each point
- Calculate the grey relational coefficient:

$$r_i(k) = \frac{\Delta_{min} + \rho \cdot \Delta_{max}}{\Delta_i(m) + \rho \cdot \Delta_{max}}$$

and ρ is the resolution coefficient.

- Solve the relevancy:

$$r_i = \frac{1}{t}\sum_{k=1}^{t} r_i(k), i = 1, 2, \cdots, n$$

- Normalize the results:

$$r_i = \frac{r_i}{\sum_{i=1}^{n} r_i(k)}, i = 1, 2, \cdots, n$$

- There are m CRs. Repeat the above steps and the correlativity from 1-m will be got and finally build the matrix of Crs-TCs

Identify importance degree of TCs:
GM (1, N) model:

$$x_1^{(0)}(k) + az_1^{(1)}(k) = \sum_{2}^{N} t_i x_1^{(1)}(k), k = 1, 2, \cdots, n$$

$x_1^{(1)}$ is AGO accumulated generating series for $x_i^{(0)}$, that is:

$$x_1^{(1)}(k) = \sum_{i=1}^{k} x_i^{(0)}(i), k = 1, 2, \cdots, n$$

$z_1^{(1)}$ is the neighboring generating series of $x_1^{(1)}$, that is:

$$z_1^{(1)}(k) = 0.5x_1^{(1)}(k) + 0.5x_1^{(1)}(k-1), k \ge 2$$

where, α and t_i are the incidence number.

Rank ordering of TCs' importance degree:

- HOQ transformation. Apply $R_{11} = r_{11} \times p_{11}$ to quantize the initial HOQ, adjust the correlativity of HOQ, reflect both of the correlativity and needs importance degree in a correlativity matrix and get the transferred HOQ
- According to the data of CRs-TCs HOQ, establish the systemic original observation data series:

$$x_1^{(0)}(k) = x_1^{(0)}(1), x_1^{(0)}(2), \cdots, x_1^{(0)}(k), k = 1, 2, \cdots n$$

If for $x_1^{(0)}$,there are m kinds of requirements in HOQ, then $x_1^{(0)} = (1, 2, \cdots, n)$.

While $x_2^{(0)} = (R_{11}, R_{12}, \cdots, R_{1m})$, similarly:

$$x_3^{(0)} = (R_{n1}, R_{n2}, \cdots, R_{nm})$$

By parity of reasoning, build the original observation data series.

- Conduct AGO series for original data, provide intermediate information for modeling, shortening the randomness of original series.

$$X^{(1)}(k) = \sum_{i=1}^{k} X^{(0)}(i), k = (1, 2, \cdots, n)$$

For example:

$$X_1^{(1)}(k) = \sum_{i=1}^{k} X_1^{(0)}(i), k = (1, 2, \cdots, n)$$

- Plug the data above into the formula of GM (1, N) and get:

$$\begin{bmatrix} X_1^{(0)}(2) \\ X_1^{(0)}(3) \\ \vdots \\ X_1^{(0)}(n) \end{bmatrix} = \begin{bmatrix} -Z_1^{(1)}(2) & X_2^{(1)}(2) & \cdots & X_N^{(1)}(2) \\ -Z_1^{(1)}(3) & X_2^{(1)}(3) & \cdots & X_N^{(1)}(3) \\ \vdots & \vdots & \ddots & \vdots \\ -Z_1^{(1)}(n) & X_2^{(1)}(n) & \cdots & X_N^{(1)}(n) \end{bmatrix} \begin{bmatrix} a \\ b_2 \\ \vdots \\ b_N \end{bmatrix} T$$

To simplify the formula, suppose that:

$$A = \begin{bmatrix} -Z_1^{(1)}(2) & X_2^{(1)}(2) & \cdots & X_N^{(1)}(2) \\ -Z_1^{(1)}(3) & X_2^{(1)}(3) & \cdots & X_N^{(1)}(3) \\ \vdots & \vdots & \ddots & \vdots \\ -Z_1^{(1)}(n) & X_2^{(1)}(n) & \cdots & X_N^{(1)}(n) \end{bmatrix}$$

$$Z = \begin{bmatrix} X_1^{(0)}(2) \\ X_1^{(0)}(3) \\ \vdots \\ X_1^{(0)}(n) \end{bmatrix}$$

- Work out the equation, get:

$$\begin{bmatrix} a \\ b_2 \\ \vdots \\ b_N \end{bmatrix} = (A^T A)^{-1} A^T Z$$

where, a and b_i are incidence number, $|b_2|, |b|_3, \cdots, |b_N|$ represent the importance weight of $TC_1, TC_2, \cdots, TC_N$, respectively, work them out that the weight of each TCs are identified. The greater the value is, the stronger impact the corresponding technical parameter has on the system and then we can gain the rank ordering of TCs weight.

SIMULATION APPLICATION

The phase of mechanical design is critical to the success of the final product and how to grasp customer needs is the key process of guiding the consequently product development. Here, we suppose that B is the product of A company, then we can apply the above-mentioned systemic analytical framework combining DQFD with GM (1, N) to the design and development progress of B in order to examine its effectiveness and efficiency.

Firstly, gain customers' needs by expert interview, literature searching and etc., abstract several requirements such as good reliability, high security, good instantaneity, strong compatibility and etc., then detail them into levels, simultaneously abstract corresponding technical characteristics from component module, thus building design planning house of quality(see Fig. 1 as schematic diagram). And then, map the technical characteristics to the design and development of each functional module, to improve product quality practically and ensure its reliability. It is important to note that the importance degree of customers' requirements in HOQ was gained by AHP (Wei *et al.*, 2005) and GST (Liu *et al.*, 2010), no expatiation here for it's not the focus of this article.

Secondly,get the correlativity coefficient which reflects the impact of each technical characteristics on the product.

Thirdly, build the systematic original series data. In this case, there are eight requirements in the HOQ, so there is:

$$x_1^{(0)}(k) = (1, 2, \cdots, 8), k = 1, 2, \cdots, 8$$

Fourthly, according to the formula above-mentioned and get AGO series of original data and:

$$x_i^{0}(k), i = 1, 2, \cdots, 8$$

Fifthly, calculate the neighboring mean generating series value in the model.

At last, plug the AGO series value of $x_1^{(0)}(k)$ and $Z_1^{(1)}$ got above into the matrix and get b_1, b_2, b_3, b_4 and b_5. Suppose $|b_5|>|b_3|>|b_2|>|b_1|>|b_4|$, that's implying the importance degree of technical characteristics is: $TC_5 > TC_3 > TC_2 > TC_1 > TC_4$, from the high to the low is TC_5, TC_3, TC_2, TC_1 and TC_4. According to the sequence of TCs' importance degree, we can know how to allocate the limited resources effectively and efficiently and then can guide the process of development and quality control of mechanical product and effectively cope with the dynamic customer requirements.

CONCLUSION

Considering the characteristics of design requirements, this paper brings QFD in, expands the traditional QFD to DQFD which can respond to needs' changes and builds a 3D-HOQ as its core. Due to the fuzziness and uncertainty of customers' needs, the author put forward a mechanical design requirements analysis framework combining DQFD with GST: use grey correlation algorithm to calculate needs importance degree and the correlativity between needs and techniques, then use grey model to assess the importance degree from a systematic aspect and get the rank ordering of technical characteristics importance degree.

This model and method is of certain scientificness and easy to be mastered and applied practically, which has universal applicability to ensure reliability of mechanical product. Aiming at the product deploying and quality-ensuring process, the author set up customers' needs-oriented design mentality to strengthen the communication between designers and users, build a knowledge base of mechanical design reliable requirements, which can provide guidance to product deployment, optimize resource allocation, balance and set priorities in the limited resources and realize maximal benefits under the constraint of resources.

While this study contributes to the literature in QFD research and Grey Theory, there are several limitations, which open up avenues for future research. First, we only put forward an analytical framework and simulation calculation in this study. By applying the analysis framework to the design and development of the practices of mechanical design in the future, which can approved whether this framework can help to lower the cost of information collection, improve the accuracy of information processing and enhance the quality and reliability of the product or not. Second, in the future research, the correlativity between requirements characteristics should be taken into account, combining QFD with DOE and TRIZ to eradicate conflicts of reliable requirements. Third, aiming at the fuzziness and uncertainty of customers' needs, Rough Set Theory, Evidence Theory and etc. can be further brought into improve the accuracy of customers' needs rank ordering and the sequential HOQ development. Fourth, the changes of some certain needs may have potential risks, which would bring fault to the mechanical product, so how to analyze and prevent such risks and faults is also a research subject for further study.

ACKNOWLEDGMENTS

This study was supported by the Major Research Plan of the National Natural Science Foundation of China under Grant No. 90718038, the National Natural Science Foundation of China under Grant No. 70472056 and the Natural Science Foundation of Zhejiang Province of China under Grant No. Y7080086.

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