A systematic method for mapping customer requirements to quality characteristics in product lifecycle

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Abstract: This paper presents a fundamental research on customer requirements modelling and propagation throughout the whole product development lifecycle. A theoretical mapping model, from customer requirements to quality characteristics, is established. It covers three processes, i.e., the qualification and classification of customer requirements, the generation and transformation of product quality characteristics, and product quality characteristics optimisation. The Analytic Network Process (ANP) approach was adopted to establish the weights of different customer requirements and product quality characteristics. Intra- and inter-relations for customer requirements and quality characteristics are modelled. Matching and conflict-resolving algorithms are proposed. A case study is also given.

Keywords: product quality characteristics; customer requirements; product design; Zero-One Goal Programming; ZOGP; mapping and analysis; Analytic Network Process; ANP.

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1 Introduction

Customer-oriented product development emphasises the roles played by customer requirements in different stages of a product's lifecycle. Customer requirements have to be systematically modelled and integrated into product design and development processes. To do so, firstly, customer requirements should be translated and mapped into product quality characteristics. Secondly, product quality characteristics must be decomposed, transformed and implemented into product design processes. Finally, they are represented with part features, dimensions, geometric relations, tolerances and material requirements. The key issue lies in how to translate and map customers' desires and tastes, i.e., customer requirements, into quality characteristics systematically and faithfully.

To achieve this objective in product development, three processes are involved; the qualification and classification of customer requirements, the generation and transformation of product quality characteristics, and product quality characteristics optimisation.

Traditionally, the House of Quality (HOQ) under the Quality Function Deployment (QFD) approach (Ulrich and Eppinger, 1995) was used to incorporate customer requirements into product design. However, the lack of a formal method to interpret the semantics of customer requirements, which are usually fuzzy and conflicting, makes the implementation of the HOQ method difficult to determine if the realisation of the product satisfies its customers' needs. Temponi et al. (1999) extended the HOQ method with a fuzzy logic-based module to qualify customer requirements and to identify the relations among them. More recently, customer requirement patterns were investigated for mass customisation and personalisation purposes. Chen et al. (2002) used a laddering technique to resemble a form of structured interview to elicit customer requirements, and a self-organised neural network algorithm to identify customer requirement patterns. Du et al. (2003) adopted a tree-structured classification algorithm to handle the complicated interrelations among customer requirements.

On the other hand, product specifications, or quality characteristics, must be clearly identified for modular design (McAdams et al., 1999), product family planning (Jiao and Tseng, 2000) and mass customisation (Jiao and Tseng, 2004). Theoretically, each of the product functional requirements, or quality characteristics, should be as independent as possible (McAdams et al., 1999), but in most cases, they are cross-related. To deal with such interdependent product functions or quality characteristics, a combined ANP (Saaty, 1996) and Goal Programming (GP) approach was proposed by Lee and Kim (2000) who used the method for information system project selection. Karsak et al. (2002) applied the same method for mapping from customer requirements to product characteristics with emphasis on the relative importance scores of these two sets' member elements. This approach has the advantage of being simple and easy to apply. However, the correlations among customer requirements and product characteristics were not fully addressed.

In the current trend of customer-oriented manufacturing, product quality characteristics become an intermediate layer of product representation which connects to detailed product engineering features (Chen, 2004) at one end, and to customer requirements at the other end. McKay et al. (2001) proposed a product representation scheme which allows the grouping of product specifications; in turn, such grouped relations reflect the customer requirements. However, the influence of customer requirements on product quality characteristics is not so straight forward. Different requirements have different levels of influence, or importance weight, to the individual quality characteristics. While many proposed solutions have been proposed on the identification of customer needs and product specifications, the mapping relationship between these two groups of product attributes has not been well studied yet (Jiao and Zhang, 2005).

Fung et al. (1998) recognised that if a company can duly transform the genuine and major customer attributes into product attributes, such as quality characteristics and the related features, it would have a distinct advantage in competition. They proposed to express the relationships between customer requirements and product characteristics with numerical terms, in the form of a hybrid system which incorporates the principles of QFD, Analytic Hierarchy Process (AHP) and fuzzy set theory for managing customer requirements. Difficulties were encountered from matrix calculation complexity when mapping these two sets of attributes in the fuzzy set rules, and also due to the lack of consideration of the inter-dependency between product characteristics. Chen and Tang (1999) have highlighted the issues that exist in the mapping process and reported some research work on this issue, but there was no systematic method suggested. Recently, Fung et al. (2002) enhanced their hybrid approach by taking the correlations among product characteristics as well as constraints, such as cost and resources, into consideration. Although their effort has given a relatively complete picture about the mapping issues, this picture is far from a clear relational map, due to the built-in shortcomings of the fuzzy set approach. It was questionable in finding the optimised customer requirements, given the complicated fuzzy membership functions used for both the customer requirement set and the product characteristics. Their proposed fuzzy QFD planning model in Fung et al. (2002) and the earlier prioritisation-based method (Bode and Fung, 1998) are not transparent when processing the mapping to the end users and hence the process is not verifiable. Therefore, a comprehensive and yet simplified and verifiable mapping method is required for customer-oriented product analysis. Jiao and Yang (2005) used an association rule mining method to discover the relations between customer requirements and product characteristics. It is a good effort to establish the mapping rules between these two sets of product attributes. However, interpreting the rules identified is not an easy task, and it might not be easily accepted by designers in a customer-oriented product development.

This work proposes a systematic mapping method, which offers two contributions:

- establishment of the intra-relations among different customer requirements and among different quality specifications, and the inter-relations between these two sets of product attributes
- a set of mapping, qualifying, conflict resolving, and optimisation algorithms, which is proposed with coherent considerations of the cost, the lead time, the usage of resources, and the feasibility.

Hence, an effective mapping from customer requirements to product quality characteristics has been realised.

2 Qualification and classification of customer requirements

Generally speaking, customers' description of their ideal product is neither precise nor systematic; very often, it is rather fuzzy with a lot of redundancy. Hence, customer requirements have to be reviewed, analysed, qualified and classified.

2.1 Overlap analysis for customer requirements and the qualification

Let $R_{C0} = \{r_{c1}, r_{c2}, ..., r_{cm1}\}$ represents the set of customer requirements, where r_{ci} $(i = 1, 2, \ldots, m1)$ is the ith customer requirement. Assume r_{ci}, $r_{cj} \in R_{C0}$, then potentially, the contents represented by r_{ci} and r_{cj} could have the following three types of relationships:

- *inclusive relation*: if the content of r_{ci} is a sub-set of r_{cj}, then r_{cj} is said to be inclusive with respect to r_{ci}
- *intersection relation*: if there is some common content between r_{ci} and r_{cj}, then r_{ci} and r_{cj} are said to be intersecting with each other
- *independent relation*: if the contents of r_{ci} and r_{cj} have no overlap, then, r_{ci} and r_{cj} are said to be independent of each other.

In the process of qualification, if inclusive relation has been detected between two requirements, then the larger one is kept while the other one is removed. If two customer requirements intersect, the overlapping contents in the requirements are extracted to form a new separate customer requirement; and at the same time they are removed from their original requirements. By doing so, redundant requirements are streamed preliminarily.

2.2 Correlation analysis and filtering

After this initial qualification process, the resulting customer requirements can be analysed to check the following for types of correlations:

- *opposite*: if r_{ci} and r_{cj} (either partially or completely) cannot be satisfied at the same time, they are said to be 'opposite' to each other
- *non-correlated*: if r_{cj} is not affected in the event that r_{ci} cannot be satisfied, they are said to be 'non-correlated'
- *conflicted*: if an increase in the degree of satisfaction to r_{ci} causes a decrease of satisfaction to r_{cj} (either partially or completely), they are said to be 'conflicted' or 'negatively correlated' with each other
- *collaborative*: if the increase in the degree of satisfaction to r_{ci} causes the increase of satisfaction to r_{cj} (either partially or completely), they are said to be 'collaborative' or 'positively correlated' with each other.

Based on the results of such analysis, customer requirements can be further streamed with necessary rephrasing and grouping. For opposite customer requirements, they are reflected and evaluated according to the product market position, targeted customer groups and the existing product quality characteristics; then the choices are made to avoid opposite correlations. The resulting customer requirement set can be represented as

$$R'_C = \{r_{c1}, r_{c2}, ..., r_{cl}\}$$

where, $r_{ci}(i = 1, 2, \ldots, l)$ is the ith customer requirement.

For all these requirements with non-correlated, conflicted, and collaborative relations, their selection is carried out according to more detailed correlation analysis as follows.

Use a matrix C to describe the correlations among these requirements.

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1l} \\ c_{21} & c_{22} & \cdots & c_{2l} \\ \vdots & \vdots & \ddots & \vdots \\ c_{l1} & c_{l2} & \cdots & c_{ll} \end{bmatrix}$$

c_{ij} is the correlation factor between the ith and the jth requirements, $(i,\ j = 1, 2, \ldots, l)$. The value of each correlation factor is assigned according to a 1-3-7 scheme. Use the integer value 1, 3, or 7 to represent a weak, medium or strong collaborative relation; and use (–1), (–3), or (–7) to represent a weak, medium, or strong conflicting relation. Integer value 0 means the no correlation between the corresponding pair of customer requirements. In the matrix, $c_{ij} = c_{ji}$, $c_{ii} = 9$.

By analysing the above correlation matrix C, the correlation index for each customer requirement can be obtained. Using r_{ci} as an example,

$$R_i = \frac{1}{c_{ii}} \sum_{\substack{j=1 \\ j \neq i}}^{l} c_{ij}.$$

For selecting customer requirements based on correlations, the following rules can be applied: if the correlation index of a customer requirement r_{ck} is larger than or equal to 1 ($R_k \leq 1$), then it means r_{ck} can be implicitly satisfied by satisfying other customer requirements; hence, r_{ck} can be removed.

On the other hand, if the correlation index of a customer requirement r_{ck} is less than or equal to –1 ($R_k \leq -1$), then it means r_{ck} is seriously conflicting with other customer requirements; then, r_{ck} should be assigned a high importance degree and has to be seriously considered in mapping processes at later stages.

2.3 Importance degree analysis and the final selection for customer requirements

This work uses an ANP method (Saaty, 1996; Lee and Kim, 2000) to determine the importance weights of each customer requirement. ANP has been widely used to determine the relative importance factors of correlated elements in multi-objective decision making.

After correlation analysis and filtering, the customer requirement set becomes:

$$R_C'' = \{r_{c1}, r_{c2}, ..., r_{cp}\}$$

where $r_{ci}(i = 1, 2, \ldots, p)$ is the ith customer requirement.

The impacts of the above expressions are considered with a weighted-importance sequence, and analysed in detail hereafter. The adopted ANP method (Lee and Kim, 2000) to determine customer requirements' importance factors is described as follows:

Step 1: Determine the weight factors of customer requirements without considering their correlations. For each, use a weight value from 1 to 9, then a sequence of weights can be derived. After unification, the customer requirements weight vector is w_r,

$$w_r = (w_1, w_2, ..., w_p)^T$$

where

$$\sum_{i=1}^{p} w_i = 1.$$

Step 2: Determine the importance degree relations among different customer requirements. Use matrix W_r to describe the importance degree relations. For example, in the case of r_{ci}, based on the consideration of relative importance relations between r_{ci} and other customer requirements, determine its relative importance scores against others, and then a relative importance matrix W_i can be found as:

$$W_i = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1i} & \cdots & r_{1p} \\ r_{21} & r_{22} & \cdots & r_{2i} & \cdots & r_{2p} \\ \vdots & \vdots & & \vdots & & \vdots \\ r_{i1} & r_{i2} & \cdots & r_{ii} & \cdots & r_{ip} \\ \vdots & \vdots & & \vdots & & \vdots \\ r_{p1} & r_{p2} & \cdots & r_{pi} & \cdots & r_{pp} \end{bmatrix}$$

where each element, $r_{ij} \in [0, 9]$, and when $r_{ji} \neq 0$, $r_{ij} = 1/r_{ji}$; and when $r_{ji} = 0$, $r_{ij} = 0$. Using the AHP method (Saaty, 2000), the vector of the relative importance scores of other customer requirements against r_{ci} can be found as:

$$w_i = (w_{1i}, w_{2i}, ..., w_{ii}, ..., w_{pi})^T,$$

where

$$\sum_{j=1}^{p} w_{ji} = 1.$$

Accordingly, the relative importance degree matrix W_r can be derived as follows:

$$W_r = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1i} & \cdots & w_{1p} \\ w_{21} & w_{22} & \cdots & w_{2i} & \cdots & w_{2p} \\ \vdots & \vdots & & \vdots & & \vdots \\ w_{i1} & w_{i2} & \cdots & w_{ii} & \cdots & w_{ip} \\ \vdots & \vdots & & \vdots & & \vdots \\ w_{p1} & w_{p2} & \cdots & w_{pi} & \cdots & w_{pp} \end{bmatrix}.$$

Step 3: Determine the importance degree of each customer requirement. Using w_c' to represent the importance degree vector, we have:

$$w_c' = W_r \times w_r = (w_{c1}, w_{c2}, ..., w_{cp})^T.$$

Step 4: Determine the qualified customer requirements according to the order of importance degree; remove those trivial ones. Eventually, the qualified customer requirement set $R_C = \{r_{c1}, r_{c2}, \ldots, r_{cm}\}$ and the corresponding unified importance score vector, which can be represented as $w_C = (w_1, w_2, ..., w_m)^T$, are obtained.

3 Product quality characteristics generation and qualification

Customer requirements have to be mapped or transformed into product quality characteristics, which are used to guide the product development activities. Assume that the initial set of quality characteristics is obtained based on the product specifications and past experience. These quality characteristics have to be analysed for correlations and importance degrees.

3.1 Quality characteristics generation

Traditionally, based on the customer requirements, product quality characteristics are created by consulting experts and engineers from different stages of the product lifecycle. Many interactive meetings are carried out, and the most common approach is based on the brainstorming method. There could be the following three types of corresponding relations between customer requirements and product quality characteristics:

- *one-to-one relation*: in this type, for a particular customer requirement, there exists one, and only one, product characteristic corresponding to it
- *one-to-many relation*: it means for one customer requirement, there are many product quality characteristics corresponding to it
- *many-to-one relation*: in this type, many customer requirements correspond to one product quality characteristic.

In comparison to customer requirements, among the resulting product quality characteristics, there are also different relations, such as inclusive, intersecting and independent types. Preliminary processes are required to deal with inclusive and intersecting quality characteristics so that redundant ones are eliminated. Then, the resulting quality characteristics still have opposite, non-correlated, conflicting and collaborative relations.

3.2 *Correlation analysis on product quality characteristics*

After the necessary analytical rationalisation and removal of opposite characteristics, the initial set of quality characteristics can be generated, i.e., $C_Q(c_{q1}, c_{q2}, \ldots, c_{qn})$, which still have non-correlated, mutually conflicting and collaborative member elements. For qualifying and selecting the final set of product quality characteristics, a correlation matrix for product quality characteristics, Q, is established; and then the correlation index for each of them is calculated.

3.3 *Analysis of importance degrees for quality characteristics*

The importance degree of each element must be considered. Due to the mutual interactions between product quality characteristics and customer requirements, and the correlations among these quality characteristics, when analysing the importance degrees, their interactions with the customer requirements, and the collaborative and conflict relations among them, must be considered. The ANP method is also used here:

- The analysis of the impact degrees between customer requirements and quality characteristics. Their impact relations can be expressed with a matrix, W_{qc}. When considering such impact relations, we assume that all the quality characteristics are independent of each other. By comparing the impacts to the individual quality characteristics by each customer requirement, an impact degree matrix can be derived using the AHP method (Saaty, 1980; Fukuda and Matsuura, 1993). For each customer requirement, the impact factor vector corresponding to all the quality characteristics can be obtained. Then the overall impact degree matrix, W_{qc}, can be created by combining all the individual customer requirements' impact vectors.
- The calculation of importance degrees for product quality characteristics. The exact same method for generating customer requirements' importance degree matrix can be applied to develop the importance degrees matrix for quality characteristics, i.e., W_q. Furthermore, the impact degree matrix with the considerations of inter-relations among quality characteristics, W_{QC}, can be derived from matrices W_{qc} and W_q, as,

  $$W_{QC} = W_q \times (W_{qc})^T.$$

Then, considering the overall impact to the product quality characteristics by customer requirements, the importance degree vector of the quality characteristics is:

$$w_Q = W_{QC} \times w_C.$$

4 Product quality optimisation and consolidation

When determining product quality characteristics, except for their importance degrees, their influence on other factors, such as cost, lead time, resources usage and feasibility must be considered. These factors can be processed as constraints, which can be further classified as quantitative constraints (such as cost and lead time) and qualitative constraints (such as feasibility and resource usage).

Due to the correlation or inter-dependency existing among product quality characteristics, their influence on the constraints must be sufficiently considered. For quantitative constraints, they have to be distributed among individual quality characteristics without the consideration of correlations first. Then, the resulting constraint values to individual quality characteristics are multiplied by the correlation coefficients obtained from the correlation analysis; so the corrected constraint values for individual quality characteristics are obtained. As to those qualitative constraints, via pairwise comparison, the weights among individual quality characteristics towards the goal of the constraint are obtained. In addition, the constraint predictability has to be considered when evaluating the correlation influences.

Using a weighted Zero-One Goal Programming (ZOGP) method as in Karsak et al. (2002), the optimum set of product quality characteristics can be achieved. The general form is described as follows:

$$\min \omega_1(d_1^-) + \sum_{i=2}^{k} \omega_i \left(\frac{d_i^-}{R_i} + \frac{d_i^+}{R_i} \right) + \sum_{i=k+1}^{m} \omega_i (d_i^-)$$

s.t.

$$\sum_{j=1}^{n} w_{Qj} x_j + d_1^- - d_1^+ = 1$$

$$\sum_{j=1}^{n} r_{ij} x_j + d_i^- - d_i^+ = R_i, \quad i = 2, \ldots, k$$

$$\sum_{j=1}^{n} w_{ij} x_j + d_i^- - d_i^+ = 1, \quad i = k+1, \ldots, m; \text{ and}$$

$$x_j \in \{0,1\}; \quad j = 1, 2, \ldots, n; \quad d_i^-, d_i^+ \geq 0; \quad i = 1, 2, \ldots, m;$$

in which,

ω_i: The weights of goals ($i = 1, 2, \ldots, m$).

d_i^-: The ith goal's negative deviation.

d_i^+: The ith goal's positive deviation.

x_j: 0–1 variable, representing the jth product quality characteristic ($j = 1, 2, \ldots, n$).

w_{Qj}: The jth product quality characteristic's important degree.

r_{ij}: The number of the ith type of quantitative constraints used by the jth product quality characteristic.

R_i: The ith quantitative constraint limit.

w_{ij}: The weight of the jth product quality characteristic over the ith qualitative constraint goal.

5 Case study

This case study uses a refrigerator as the example product. According to customer requirements, and considering the total cost, the time to market, current resources utility, and the feasibility, eventually the quality characteristics for the product improvement are determined.

Based on the collected information from customers by the sales department, after screening and proper articulation, six customer requirements are determined by the company:

- high freezing power (r_{c1})
- excellent effect of fast freezing to keep food freshness (r_{c2})
- high reliability (r_{c3})
- low power consumption (r_{c4})
- large effective storage volume (r_{c5})
- low usage cost (r_{c6}).

Step 1: Develop the correlation matrix C by analysing the relations among customer requirements:

$$C = \begin{bmatrix} 9 & 7 & 0 & -1 & 0 & -1 \\ 7 & 9 & 0 & -1 & 0 & -1 \\ 0 & 0 & 9 & 0 & 0 & 7 \\ -1 & -1 & 0 & 9 & -1 & 7 \\ 0 & 0 & 0 & -1 & 9 & -1 \\ -1 & -1 & 7 & 7 & -1 & 9 \end{bmatrix}.$$

The correlation index can be worked out as shown in Table 1.

Table 1 Correlation indices for different customer requirements

	r_{c1}	r_{c2}	r_{c3}	r_{c4}	r_{c5}	r_{c6}
R_i	0.56	0.56	0.78	0.44	–0.22	1.22

It can be observed that 'Low usage cost' has strong positive correlation with 'low power consumption' and 'high reliability'; but there is no correlation between 'low power consumption' and 'high reliability'. At the same time, the requirement of 'Low usage cost' does not strongly conflict with any of other customer requirements, and it has a correlation index of 1.22 ($1.22 > 1$). It indicates that this customer requirement, i.e., 'Low usage cost', can be implicitly satisfied when other constraints are satisfied. So the customer requirement set becomes $R'_c = (r_{c1}, r_{c2}, r_{c3}, r_{c4}, r_{c5})$.

Step 2: Analysis of the relative importance degrees for customer requirements.

- Determine the relative weights of customer requirements. Assume all the five customer requirements are non-correlated. Each weight is represented with a score in the range from 1 to 9. Comparison among the five customer requirements worked out as:

  $$(r_{c1}, r_{c2}, r_{c3}, r_{c4}, r_{c5}) = (3, 9, 5, 7, 1).$$

  After unification, the corresponding weight vector for the customer requirements, w_r, can be worked out as:

  $$w_r = [0.12, 0.36, 0.20, 0.28, 0.04]^T.$$

- Determine the importance degree relation matrix for the customer requirements.

  $$W_r = \begin{bmatrix} 0.643 & 0.283 & 0.000 & 0.096 & 0.000 \\ 0.283 & 0.643 & 0.000 & 0.080 & 0.239 \\ 0.000 & 0.000 & 1.000 & 0.000 & 0.000 \\ 0.074 & 0.074 & 0.000 & 0.558 & 0.138 \\ 0.000 & 0.000 & 0.000 & 0.266 & 0.623 \end{bmatrix}.$$

- Calculate the importance weight factors with the consideration of correlations w'_C

  $$w'_C = W_r \times w_r = [0.206, 0.297, 0.200, 0.197, 0.100]^T.$$

  Since there is no correlation index that is less than –1, the adjustment to importance weight factors is not required. Then the final customer requirement set is

  $$R_c = (r_{c1}, r_{c2}, r_{c3}, r_{c4}, r_{c5}),$$

  and the weight factor vector remains as

  $$w_C = [0.206, 0.297, 0.200, 0.197, 0.100]^T.$$

Step 3: Identify product quality characteristics.

After consulting the experts from different aspects, preliminary analysis and screening, six product quality characteristics are determined:

- increasing compressor power (c_{q1})
- using new thermal isolation material (c_{q2})
- using highly sensitive transducer (c_{q3})
- increasing the average fault-free life span (c_{q4})
- enhancing the layout of the cooling channels (c_{q5})
- reducing the volume of the compressor (c_{q6}).

To obtain the optimum set of product quality characteristics to be focused on according to our proposed mapping method, the detailed procedures are described hereafter.

Step 4: Correlation analysis among product quality characteristics.

By analysing the correlations among quality characteristics, the correlation matrix *Q* can be obtained as follows:

$$Q = \begin{bmatrix} 9 & 0 & 0 & 0 & 0 & -3 \\ 0 & 9 & 0 & 0 & 0 & 0 \\ 0 & 0 & 9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 9 & 0 & 0 \\ 0 & 0 & 0 & 0 & 9 & 0 \\ -3 & 0 & 0 & 0 & 0 & 9 \end{bmatrix}.$$

Then the correlation indices of the quality characteristics are shown in Table 2.

Table 2 Correlation indices for different quality characteristics

	C_{q1}	C_{q2}	C_{q3}	C_{q4}	C_{q5}	C_{q6}
R_i	–0.33	0	0	0	0	–0.33

Step 5: Relative importance degree analysis for quality characteristics.

As proposed previously, the following steps are to calculate the importance degrees for individual quality characteristics, i.e., w_Q.

- Determine mutual impact factor matrix between customer requirements and product quality characteristics:

$$W_{qc} = \begin{bmatrix} 1.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.537 & 0.305 & 0.105 & 0.000 & 0.053 & 0.000 \\ 0.000 & 0.000 & 0.000 & 1.000 & 0.000 & 0.000 \\ 0.072 & 0.232 & 0.000 & 0.000 & 0.696 & 0.000 \\ 0.088 & 0.244 & 0.000 & 0.000 & 0.000 & 0.668 \end{bmatrix}.$$

- Determine the importance degree relation matrix for the quality characteristics.

$$W_q = \begin{bmatrix} 0.648 & 0.000 & 0.000 & 0.000 & 0.062 & 0.250 \\ 0.000 & 0.750 & 0.000 & 0.000 & 0.267 & 0.000 \\ 0.000 & 0.000 & 0.833 & 0.000 & 0.108 & 0.000 \\ 0.000 & 0.000 & 0.000 & 1.000 & 0.000 & 0.000 \\ 0.122 & 0.250 & 0.167 & 0.000 & 0.563 & 0.000 \\ 0.230 & 0.000 & 0.000 & 0.000 & 0.000 & 0.750 \end{bmatrix}.$$

- Calculate the importance degree vector for quality characteristics w_Q with the consideration of correlations among the customer requirements and quality characteristics, respectively.

$$w_Q = [W_q \times (W_{qc})^T] \times w_c = [0.278, 0.161, 0.042, 0.200, 0.179, 0.140]^T.$$

Step 6: Consider quantitative constraints.

In this example, four additional constraints are considered, i.e., the cost for the enhancement, the time required to roll out the new product, the existing resource utilisation, and the feasibility. The cost and the time to market are considered as quantitative constraints. It is desirable that the cost involved should be low while the time to market should be short. The other two constraints, i.e., the existing resources utilisation and the feasibility, are two qualitative constraints. For these constraints, the higher their values, the better it is.

- *Considering quantitative constraints*. It is required that the unit cost incurred due to the improvement should not exceed US$100, and the time to market is limited to 36 days. Table 3 gives the unit costs and implementation times required for different quality characteristics before the overall optimisation process. It is shown that both the cost and time to market have exceeded the constraint requirements.

Table 3 Unit costs and implementation times for different quality characteristics

	C_{q1}	C_{q2}	C_{q3}	C_{q4}	C_{q5}	C_{q6}
Unit cost (US$)	30	15	10	15	10	25
Time required (day)	10	6	5	5	4	8

Considering the correlations among quality characteristics, the actual cost and time required index for each of the quality characteristics is changed from (1, 1, 1, 1, 1, 1) to (1.33, 1, 1, 1, 1, 1.33), so the actual unit costs and times required for different quality characteristics, i.e., c' and t', are expressed as following vectors respectively:

$$c' = [40.0, 15.0, 10.0, 15.0, 10.0, 33.3]^T$$
$$t' = [13.3, 6.0, 5.0, 5.0, 4.0, 10.7]^T.$$

- *Consider qualitative constraints*. In this given example, two more constraints, the existing resources usage and the feasibility, have to be incorporated. In order to take these qualitative constraints into consideration, they must be quantified. By using a 'paired comparison' technique, the relative weights in these two constraints are expressed as two vectors, denoted as w_R and w_F, respectively. Here, they are generated based on experts' input:

$$w_R = [0.053, 0.178, 0.121, 0.239, 0.332, 0.077]^T$$
$$w_F = [0.252, 0.173, 0.340, 0.056, 0.097, 0.082]^T.$$

Step 7: Overall optimisation for the selection of product quality characteristics.

Determine the relative weights of different goals and constraints. Again, by using 'paired comparison', the results shown in Table 4 can be derived, in which RMC means the very goal of mapping from customer requirements to quality characteristics.

Table 4 The relative weights of the goal and constraints

	RMC	*Cost c (US$)*	*Time to market t (day)*	*Resources usage r (%)*	*Feasibility f (%)*	*Relative weights ω_r*
RMC	1	1/3	1/2	2	1/3	0.117
Cost *c* (US$)	3	1	2	3	1/2	0.273
Time to market *t* (day)	2	1/2	1	2	1/2	0.176
Resources usage *r* (%)	1/2	1/3	1/2	1	1/2	0.098
Feasibility *f* (%)	3	2	2	2	1	0.336

Using the results of the above-mentioned steps, the following ZOGP model can be established. The details are provided as follows:

$$\min 0.117d_1^- + (0.273/100)d_2^+ + (0.176/36)d_3^+ + 0.098d_4^- + 0.336d_5^-$$

s.t.

$$0.278x_1 + 0.161x_2 + 0.042x_3 + 0.200x_4 + 0.179x_5 + 0.140x_6 + d_1^- - d_1^+ = 1$$

$$40.0x_1 + 15.0x_2 + 10.0x_3 + 15.0x_4 + 10.0x_5 + 33.3x_6 + d_2^- - d_2^+ = 100$$

$$13.3x_1 + 6.0x_2 + 5.0x_3 + 5.0x_4 + 4.0x_5 + 10.7x_6 + d_3^- - d_3^+ = 36$$

$$0.053x_1 + 0.178x_2 + 0.121x_3 + 0.239x_4 + 0.332x_5 + 0.077x_6 + d_4^- - d_4^+ = 1$$

$$0.252x_1 + 0.173x_2 + 0.340x_3 + 0.056x_4 + 0.097x_5 + 0.082x_6 + d_5^- - d_5^+ = 1$$

where

$$x_j \in \{0,1\}, \quad j = 1, 2, \cdots, 6; \quad d_i^-, d_i^+ \geq 0, \quad i = 1, 2, \cdots, 5.$$

The above ZOGP can be resolved by using LINDO software, and the results are shown in Table 5.

Table 5 ZOGP model results

	C_{q1}	C_{q2}	C_{q3}	C_{q4}	C_{q5}	C_{q6}
Results	0	1	1	1	1	1

Finally, the selected optimum quality characteristics are to: use new thermal isolation material (c_{q2}), use a highly sensitive transducer (c_{q3}), increase the average fault-free life span (c_{q4}), improve the cooling channel layout (c_{q5}), and reduce the volume of the compressor (c_{q6}). The cost for the implementation of these quality characteristics is US$83.3, the implementation time is 30.7 days. Under these conditions, the resource utilisation and the feasibility are optimum, with the smallest mapping errors.

6 Conclusions

This paper proposes a systematic method to map customer requirements into product quality characteristics in product design. This method includes three steps, i.e., customer requirements qualification and classification, generation of product quality characteristics, and quality characteristics optimisation and consolidation. This method can achieve maximum customer satisfaction with certain quantitative and qualitative constraints. The ANP (Saaty, 1996) approach has been applied to determine the importance weights among customer requirements and quality characteristics. All the intra- and inter-relations of these two sets of product attributes, either complimentary or contradicting ones, are considered thoroughly. In order to increase the accuracy of the mapping results, in the optimisation and final consolidation of quality characteristics, a model of ZOGP (Lee and Kim, 2000; Karsak et al., 2002) is used to balance the constraints, such as cost, lead time, the usage of existing resources and the feasibility.

In comparison with Fung et al.'s (1998, 2002) approach, this method has the advantage of being explicit and verifiable, hence it is easier to be applied and evaluated. Referring to Karsak et al. (2002), the proposed model has expanded the ANP-based ZOGP approach to include correlations among customer requirements and quality characteristics, as well as the relative importance degrees. The scope of application has also been increased such that the qualification and the selection of customer requirements and quality characteristics are supported. Hence, this model is more readily applicable to incorporate experience knowledge from the experts involved. The case study presented has shown that this method is an effective and efficient solution to enhance product design quality.

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