

Research Article

Preference Evaluation System for Construction Products Using QFD-TOPSIS Logic by Considering Trade-Off Technical Characteristics

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Received 29 August 2016; Accepted 30 October 2016; Published 26 January 2017

Academic Editor: Anna M. Gil-Lafuente

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This paper investigates the feasibility of quality function deployment, technique for the order of preference by similarity to ideal solution (QFD-TOPSIS) in presenting user preferences for multiple alternatives, such as construction technologies, products, systems, and design solutions, with trade-off technical characteristics (TC). The original QFD as house of quality (HOQ) defines the requirements and features as subjective matrix relations, which cause interpretations to vary across users and limit its industrial applications. QFD-TOPSIS is a new model that combines the benefits of QFD with those of TOPSIS, maintains the subjectivity and objectivity evaluation of the technical characteristics (TC), and rates the preferences by considering users' individual propensity for requirements. In addition, QFD-TOPSIS rates the preferences through the reciprocal compensation effects of trade-off TC and filters unsuitable alternatives with predefined restrictive conditions. Trade-off refers to conflicts and/or contradictions between attributes, often arising in multicriteria decision-making. Users or project stakeholder groups define the priorities of trade-off TC that directly influence product preferences and decision-making. In the present study, we have developed a Web system based on the QFD-TOPSIS logic and tested its operation to verify its industrial applicability and viability for automatic quality evaluation.

1. Introduction

Decision-making refers to the identification and selection of the best solution among several alternatives based on various factors reflecting the decision-maker's expectations [1].

The complex interrelationships that exist among various selection criteria make material selection a challenging and time-consuming task for designers [2]. The designers and project participants involved in construction work require decision-making processes for suitable selections from numerous designs, technologies, and product solutions. Suitable decision-making in construction work of the required quality reduces the design changes because unsuitable and dissatisfactory design solutions are recognized and eliminated during the design stage; therefore, the productivity of the construction project is improved.

In terms of the technologies or products of construction projects, the quality evaluation process starts with an analysis of multiple technical characteristics (TC) and criteria. When the quality of a product is being evaluated, a conflict may often occur such that the improvement of one TC could lead to degradation of other characteristics. Although an ideal solution involves the achievement of the highest level for all attributes, in real-world applications, one of the attributes may be limited by the others.

Presently, the occurrence of preference-related issues in the trade-off problem occurs inevitably due to the noncommensurable characteristics among the concerned attributes; therefore, the value of the compensation effect should be considered from the viewpoint of the required functions that are simultaneously lost and secured. Trade-off problems have been appearing in a variety of industries [3–5].

Various mathematical models have been proposed for multicriteria decision-making (MCDM), including analytic hierarchy process (AHP, 1970s) [6], additive ratio assessment (ARAS, 2010) [7], best-worst method (BWM, 2015) [8], characteristic-objects method (COMET, 2014) [9], complex proportional assessment of alternatives (COPRAS, 1996) [10], dominance-based rough-set approach (DRSA, 2001) [11], evaluation based on distance from average solution (EDAS, 2015) [12], elimination and choice translating reality: elimination et choix traduisant la realite (ELECTRE, 1960s) [13], evidential-reasoning approach (ER, 1976) [14], gray relational analysis (GRA, 2007) [15], multiattribute utility theory (MAUT, 1970s) [16], multiobjective optimization on the basis of ratio analysis (MULTIMOORA, 2006) [17], preference ranking organization method for enrichment evaluation (PROMETHEE, 1982) [18], stochastic multicriteria acceptability analysis (SMAA, 2001) [19], superiority and inferiority ranking (SIR, 2004) [20], TODIM (an acronym in Portuguese of Interactive and Multicriteria Decision-Making, 2014) [21, 22], technique for the order of preference by similarity to ideal solution (TOPSIS, 1981) [23–25], and *ViseKriterijumska Optimizacija I Kompromisno Resenje* (VIKOR, 1979) [26, 27]. ARAS, COPRAS, EDAS, ELECTRE, MULTIMOORA, and TODIM are similar methods with TOPSIS from a structural perspective. The MCDM models have been applied to optimal selection problems in various industrial and engineering fields.

Among the MCDM methods, quality function deployment (QFD), TOPSIS, and MAUT address the abovementioned trade-off problem. QFD is a tool that can be used to define effectively the trade-off characteristics of a product. Here, the TC of the trade-off are only clarified using the house of quality (HOQ) model, and the value of the trade-off is not measured quantitatively in view of the compensation effect. TOPSIS only evaluates preferences in terms of TC and does not specify the trade-off problem. MAUT is a structured methodology that is designed to handle trade-offs among multiple objectives. One of the first applications of MAUT involved a study of alternative locations for a new airport in Mexico City during the early 1970s [28].

In terms of the trade-off problem, MAUT sets an environment of uncertainty and thus evaluates the preference of each user according to an uncertainty/risk-based approach; therefore, MAUT is not suitable for real-world applications because quality evaluation of technologies and products should produce both objective and quantitative results.

This study proposes the QFD-TOPSIS model in which the QFD model is combined with TOPSIS to measure trade-off TC. The QFD-TOPSIS model specifies the trade-off TC and analyzes the preferences by comparing common TC of multiple product solutions. If the trade-off is specified in relation to TC, intercompensation effects based on the users' weights are determined. Furthermore, the weights can be modified according to the user environment.

This case study is a follow-up of our previous work “QFD-Based Benchmarking Logic Using TOPSIS and Suitability Index” [29].

2. QFD and TOPSIS

2.1. Theory and Limitation of QFD. As described by Dr. Akao, QFD is a “method to transform qualitative user demands into quantitative parameters, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process.” [30]. Akao originally developed QFD in Japan in 1966 by combining his work on quality assurance and quality control with the function deployment approach used in value engineering.

The extent of the areas in which QFD has been researched has become so exhaustive that Carnevali and Miguel (2008) investigated QFD research as a research topic itself [31]. In particular, the QFD model has been applied to a variety of industrial fields for which the focus is MCDM. QFD is recognized as an excellent tool that allows for a comprehensive assessment of quality in consideration of multiple performance attributes and gathers the project stakeholder requirements [32].

QFD for decision-making has been commonly studied in combination with other decision-making models, for example, a decision-making model that combines QFD and fuzzy theory [33–37]; a decision-making model that combines fuzzy-based QFD and the analytic network process (ANP) [38]; and a decision-making model that combines QFD and ANP [39]. Furthermore, the Kano [40], DEA [41], rough set [42], Simple Multiattribute Rating Technique (SMART) [43], conjoint analysis [44], Multiattribute Value (MAV) [45], and Fuzzy Analytic Hierarchy Process (FAHP) [37] models have all been used in QFD for the design of quality assessment methods, where the focus is on relative comparison among the products.

Although studies on QFD are currently underway, reviews of the literature have noted difficulties in the use of quality plans according to QFD [31]. The major methodological difficulties here are related to the stage of elaboration of the quality matrices, for example, “interpreting the customer voice” [46], “identifying the most important customer demands” [47], and “project decision making, since correlations among the demands are not clear” [36]. It has been noted that alleviating the methodological difficulties in the development of the quality matrix is a key factor in encouraging and expanding the use of QFD [31].

In particular, a problem arises when different quality assessment results are derived depending on the quality matrix that is applied for the house of quality (HOQ). This fundamental cause of different evaluation results has led to the subjective creation of the “HOQ quality matrix.”

According to the original design, the creation of the “HOQ of QFD” should be based on user experience. The customer needs with regard to the “what” can be crosschecked against the related design TC of the “how.” The core matrix of QFD of HOQ is shown in Figure 1 [48].

2.2. Theory and Limitation of TOPSIS. Being a type of MCDM, TOPSIS presents the preferences of alternative solutions. TOPSIS is usually employed for relative comparison of alternatives [23, 49]. It calculates a value that represents the distance between a positive ideal solution (PIS) and a negative ideal solution (NIS). Hwang and Yoon (1981) [23]

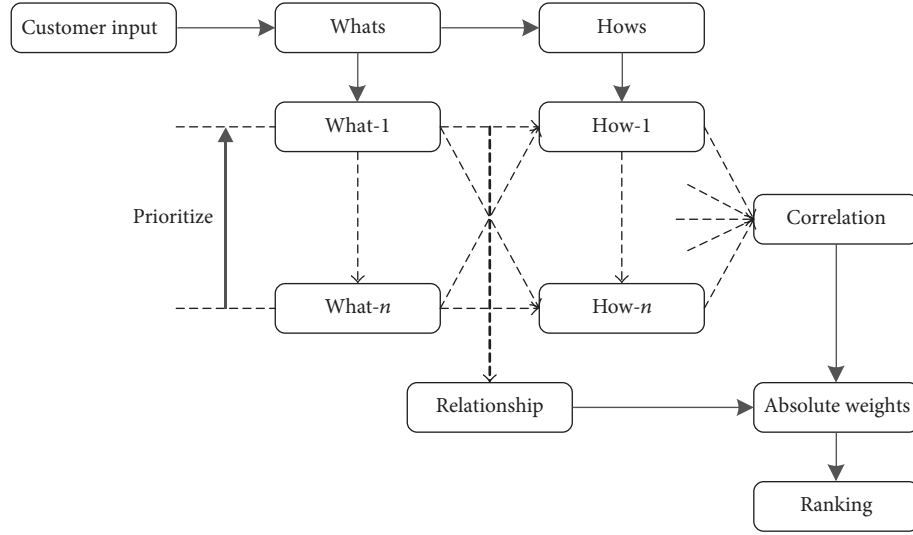


FIGURE 1: Conceptual map of the original QFD matrix.

originally proposed the TOPSIS method for the identification of solutions from a finite set of alternatives. The details of the traditional TOPSIS solution have been presented by Li et al. [50].

TOPSIS assigns preference ranks while considering multiple properties of a product, service, or system. The preference refers to scores that are distributed between 0 and 1. The quality improves as the preference score approaches 1. An assumption made with regard to TOPSIS is that the criteria are monotonically increasing or decreasing. TOPSIS requires normalization, because the parameters or criteria of the products generally consist of incongruous dimensions [51, 52].

TOPSIS, as a compensatory method, allows for trade-off solutions, where poor performance of one attribute can be negated by sound results of another attribute. This approach provides more realistic evaluation results than non-compensatory methods. TOPSIS is based on the following assumptions:

- (1) The value of each criterion is linearly decreasing or increasing.
- (2) The criteria are independent.

In contrast to the above assumptions, the trade-off criterion itself is a dependent relation between the criteria. The values are determined to be associated with each other. TOPSIS considers the trade-off problem internally only; it does not represent the trade-off directly. Therefore, it is difficult for the user to determine which criteria are more important in the trade-off problem.

The advantage of the denotation of the trade-off relationship is that the user helps to prioritize trade-off TC in consideration of the project environment. This function allows the decision maker (DMr) to select the best solution

through users' customized weights while keeping the objective evaluation value of TC.

3. QFD-TOPSIS Model

3.1. Apply Compensation Effect to Trade-off TC. This study proposes an advanced model of a preference evaluation system considering the trade-off TC problem through a combination of QFD and TOPSIS benefits. Although QFD-HOQ is a powerful tool for product quality planning, it is not directly applied to alternatives evaluation, comparison, and value engineering (VE). In contrast, TOPSIS is a straightforward and strong tool for trade-off issues and alternatives comparison. Both QFD and TOPSIS are based on TC. Thus, both can draw on the common TC to integrate the respective models into one and apply the compensation effects as defined trade-off TC.

A TC of trade-off is defined by a pair of TC that are in conflict with each other. In the trade-off of TC, the value of one TC approaches a negative value as the value of the other TC approaches the ideal value. In general, a trade-off is defined as a relationship between a pair of TC; however, a conflict may occur within one of the TC itself when the TC has two different functions.

Trade-off TC is presented in the form of correlation functions such as those given by (1)–(3) below. The trade-off values distinguish the corresponding distance interval for each TC and use at least one of the following equations for each distance interval:

$$y(x_{ij}) = a - b * \exp(cx_{ij}), \quad (1)$$

(monotone increasing, toward minimum x value),

$$y(x_{ij}) = a - b * (x_{ij}), \quad (2)$$

(inverse proportion, when $b = 1$),

$$y(x_{ij}) = a + b * \exp(cx_{ij}), \quad (3)$$

(monotone decreasing, toward maximum x value).

Here, a and b are positive constants such that “ $y(x)$ is 0 or a positive constant.” Furthermore, c is a positive constant such that $0 < c < 1$.

Figure 2 shows the preference measurement approach applied to the effect of compensation in trade-off TC using the combined QFD and TOPSIS logic.

3.2. Relationship of Function, TC, and TC Criteria. In real-world applications, the functions and TC of products may be represented as $n : n$ relationships. This method is used in the original QFD-HOQ.

Figure 3 shows the $n : n$ relationships among the function class, TC class, and TC criteria of a product by an overlapping map of QFD-HOQ. Based on Figure 3, the relationship of the relevant class is described as follows:

- (1) The function factor of $f(4)$ is associated with the TC(master) of D in a 1:1 relationship, and $f(4)$ is simultaneously composed of the elements of function C.
- (2) One function element can have one or one more TC elements.
- (3) In addition, the function class of one TC is different from that of another TC, that is, theoretically, a unique function class applies to only one TC(master) element.
- (4) The TC are all independent except for the trade-off TC.
- (5) TC(B) and TC(C) form a pair of trade-off TC.
- (6) TC(E) has a self-contradictory trade-off, as it has two different functions: F(6) and F(7).

The $n : n$ relational structure of the function and TC has itself limitations with respect to objectivity because each user would define matrix in QFD-HOQ differently. This leads to different quality planning and evaluation for the end user. In TC evaluation, however, the 1:1 relationship of function and TC enables each user to maintain consistent interpretations and to share objectivity.

The TC can be used as common class in QFD and TOPSIS. The TC always apply an objective analysis to any user. Thus, it is possible to define TC as a unique (inherent) attribute and to define the function from the TC perspective. Until now, from the view of the function, the function can have multiple TC elements. It leads to the result in the subjective matrix in HOQ. However, the way of the unique TC definition can be defined as not only a single function element but also multiple function elements. It can lead to the result in the objective matrix in HOQ.

Figure 4 shows a conceptual schematic diagram, where the TC(master) class is broken down into sublevel TC(sub). Here, every TC(sub) has a 1:1 relationship with a unique (inherent) function element or component. In addition, it is possible to specify the trade-off TC at the TC(sub) level. Figure 4 shows the denotation of the trade-off relations among the TC and the self-contradictory trade-off relation in one TC(master) by creating pairs of TC(sub).

3.3. QFD Deployment for QFD-TOPSIS. QFD is not just intended for application of HOQ. HOQ is no more than a sample among the development models of QFD. The original QFD starts from HOQ and then develops again in each production step. QFD enables the design of quality into a product in a formalized manner through four main planning stages: product, parts, manufacturing process, and production operations planning [53]. The original approach, called the “matrix of matrices,” relies on a rectangular arrangement of data into rows and columns for the organization, analysis, and development of information relating to a product being considered for design [54].

The deployment of QFD-TOPSIS consists in four steps referenced from the original QFD approach. The first step configures the HOQ using function requirements and TC. The second step sets up the 1:1 relation with TC(sub), defines the trade-off TC(sub), and determines the correlation function of the trade-off TC(sub). The third step builds a matrix of multiple alternatives from a market product, target values, and thresholds of TC(sub). The fourth step builds a weighted TC matrix for preference analysis. Figure 5 shows the 4-step conceptual schematic diagram in order to complete QFD-TOPSIS starting from HOQ.

The matrix items of QFD-TOPSIS are described as follows:

- (a) F . weight: determines the function weight of a product. The weight lies between 0 and 10.
- (b) Limit: defines the limit value of TC(sub).
- (c) Normalization value: intercompares market products by normalizing the TC(sub) values. The normalized values lie between 0 and 1.
- (d) Market products: list the market products that are to be compared as design alternatives.
- (e) Positive ideal value and negative ideal value: define the positive ideal value and negative ideal value of TC(sub).
- (f) Product preference: analyzes the preferences of market products. The values of the preferences lie between 0 and 1; the closer the value is to 1, the higher the preference is.
- (g) Target: defines the target value of TC(sub).
- (h) TC relation: denotation of the trade-off between TC(sub) that is a self-contradictory trade-off or a pair of trade-off TC.
- (i) TC(master): defines the concept of upper classification regarding TC of a product.
- (j) TC(sub): defines the concept of subclassification regarding TC of a product.
- (k) TC weight: determines the weight of TC(sub) corresponding to the product. The weight lies between 0 and 10.
- (l) Restriction filter: a TC(sub) is considered an unfit feature when it is consistent with the restrictive condition. Any unsuitable feature is excluded from the alternatives for selection.

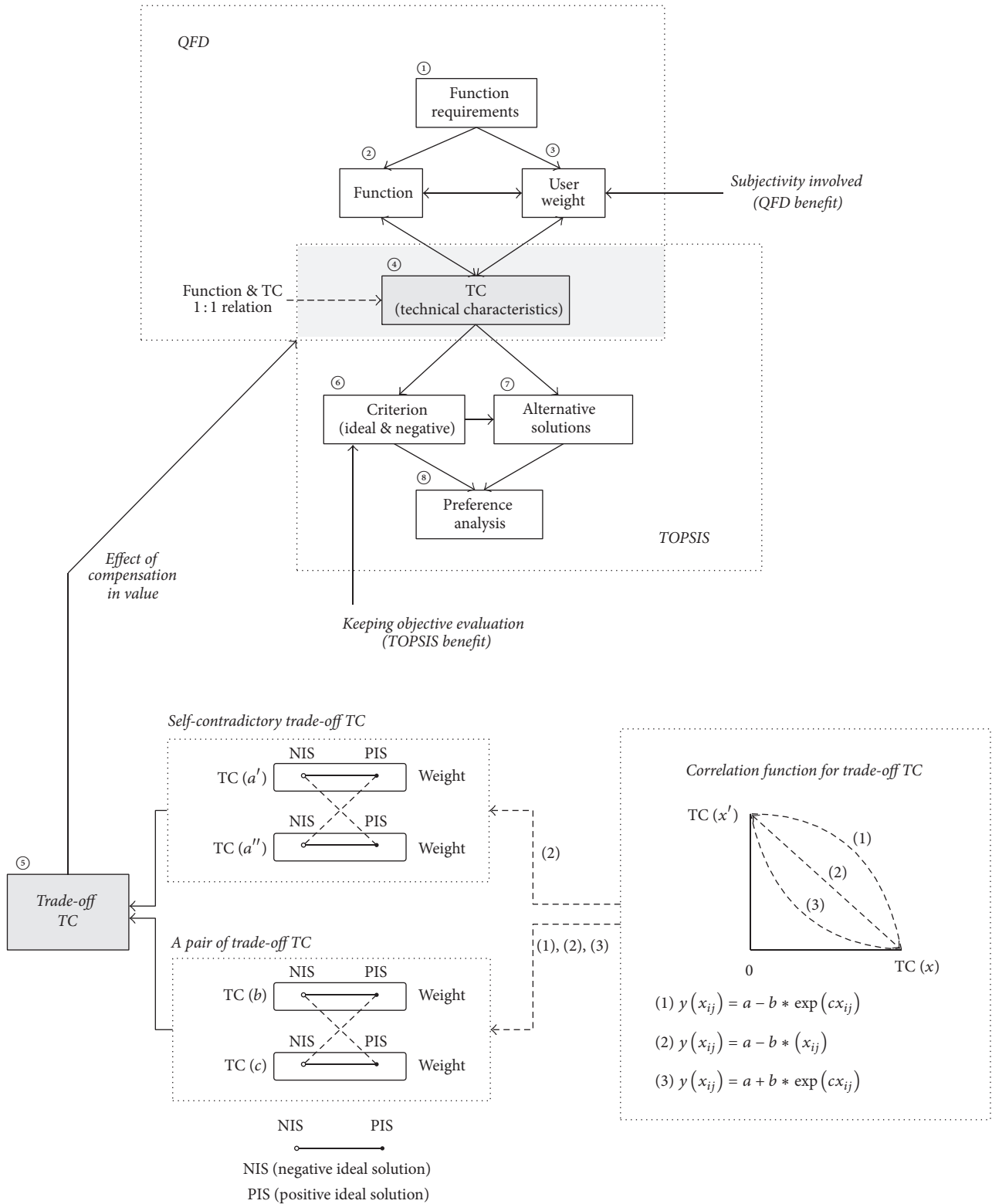


FIGURE 2: Preference evaluation model in a trade-off TC problem using the combined QFD and TOPSIS benefit.

Relation matrix of function and TC in QFD-HOQ

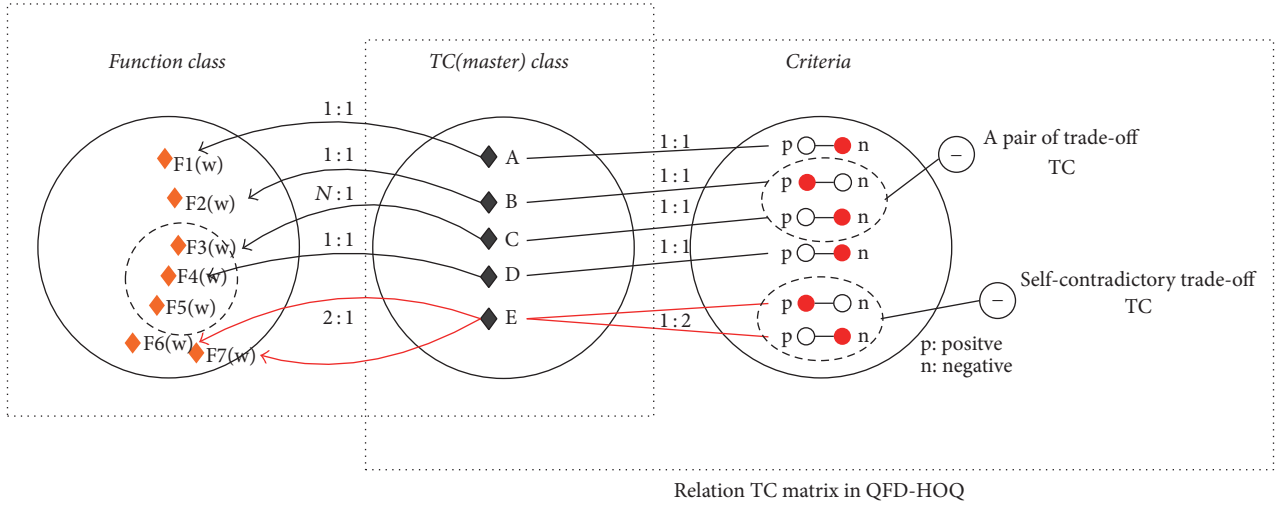


FIGURE 3: The original QFD-HOQ approach in terms of relationships and trade-off.

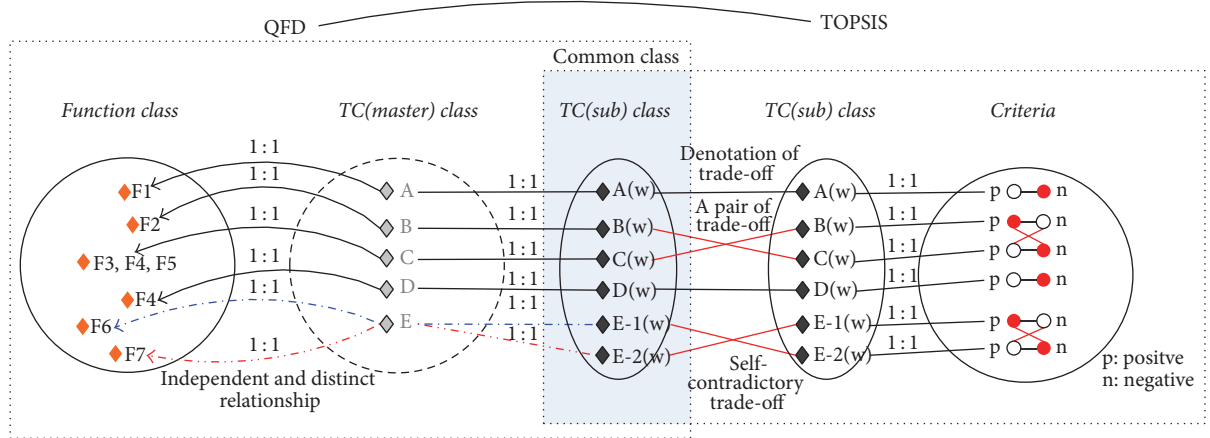


FIGURE 4: Explicit expression for a pair of trade-off TC(sub) and self-contradictory trade-off TC(sub).

4. QFD-TOPSIS Mathematical Logic

The logic of QFD-TOPSIS is as follows.

Step 1 (defining m alternative products and n units of "TC(master)"). The cross-matrix D is composed of n units of TC with respect to m units of products, a targeting alternative, and a limited alternative.

$$D = \begin{matrix} & X_1 & X_2 & \cdots & X_n \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ \vdots \\ A_m \\ A_g \\ A_l \end{matrix} & \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \\ x_{g1} & x_{g2} & \cdots & x_{gn} \\ x_{l1} & x_{l2} & \cdots & x_{ln} \end{bmatrix} \end{matrix} \quad (A_i : i = 1, 2, \dots, m, X_j : j = 1, 2, \dots, n) \quad (4)$$

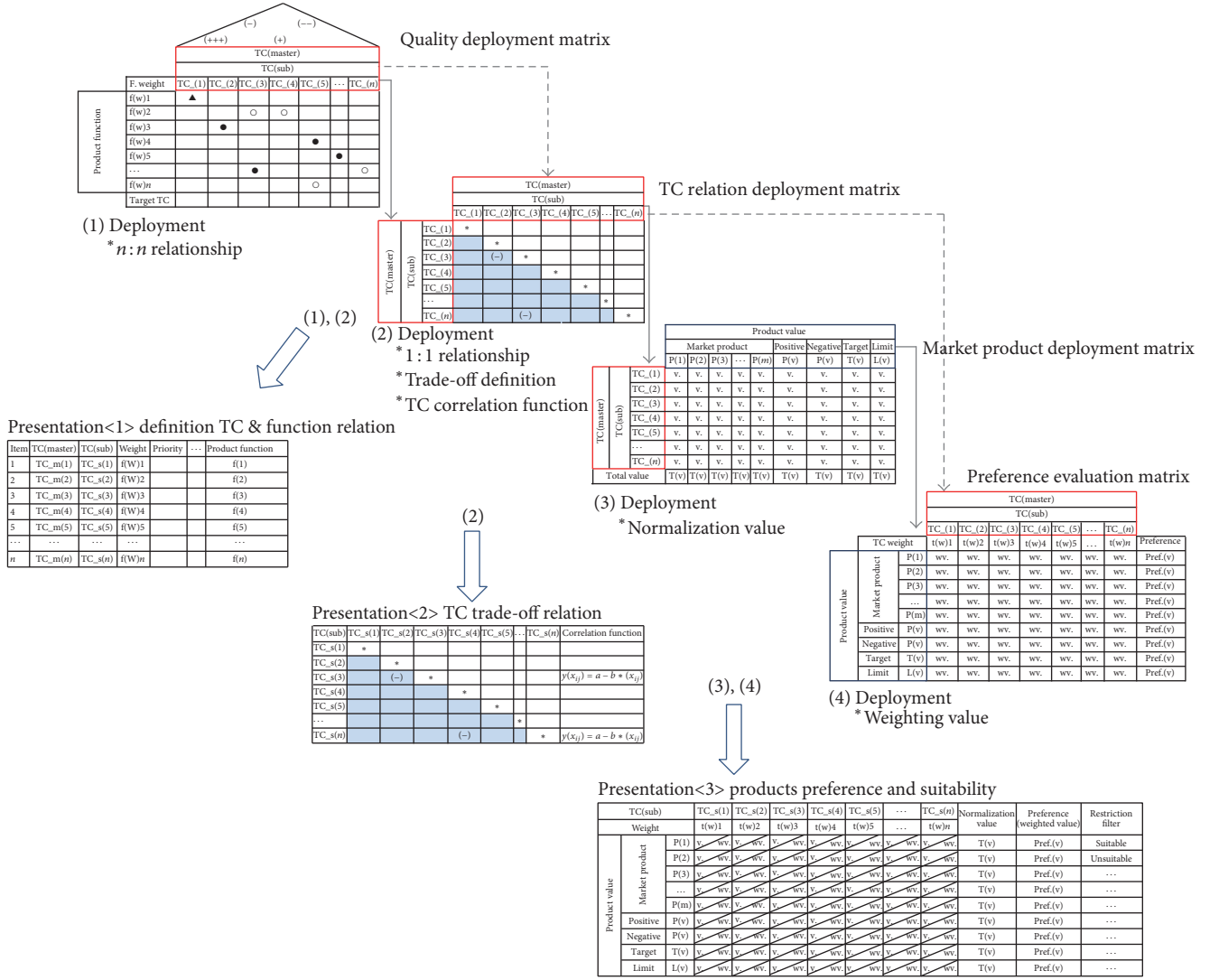


FIGURE 5: QFD deployment for the QFD-TOPSIS model.

In (4), A_i denotes the i th “product,” X_j denotes the j th “TC(master)” of the relevant product, X_{ij} denotes product A_i of the j th “TC(master) value,” A_g denotes the “target product” with the “target value of TC(master),” and A_l denotes the “limit product” with the “limit or minimum value of TC(master).” Here, i can define up to m units and j up to n units.

Step 2 (setting k units of TC(sub) dependent on TC(master) existence of the self-contradictory trade-off).

$$D' = \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ \vdots \\ A_m \end{bmatrix} \begin{bmatrix} X'_1 & X'_2 & \cdots & X'_k \\ x'_{11} & x'_{12} & \cdots & x'_{1k} \\ x'_{21} & x'_{22} & \cdots & x'_{2k} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ x'_{m1} & x'_{m2} & \cdots & x'_{mk} \end{bmatrix}$$

$$(A_i : i = 1, 2, \dots, m, X'_j : j = 1, 2, \dots, k)$$

$$A_g \begin{bmatrix} x'_{g1} & x'_{g2} & \cdots & x'_{gk} \\ x'_{l1} & x'_{l2} & \cdots & x'_{lk} \end{bmatrix}.$$

(5)

In 2, X'_j denotes the j th “TC(sub) of the relevant product.” For “TC(sub),” j can define up to k units. Furthermore, k increases by the number of self-contradictory trade-offs of X_j for TC(master); therefore, k is always greater than or equal to n ($k \geq n$). In addition, x'_{ij} denotes the j th TC(sub) value as the raw value in product A_i .

Step 3 (setting ideal and negative value and target and limit value of “TC(sub)”). The ideal value D^+ and the negative value D^- are defined as follows:

$$\begin{aligned}
D^+ &= \left\{ \left\langle \max(x'_{ij} \mid i = 1, 2, \dots, m) \mid j \in J^+ \right\rangle, \right. \\
&\quad \left. \left\langle \min(x'_{ij} \mid i = 1, 2, \dots, m) \mid j \in J^- \right\rangle \right\} = \{x_j^+ \mid j \\
&\quad = 1, 2, \dots, k\}, \\
D^- &= \left\{ \left\langle \min(x'_{ij} \mid i = 1, 2, \dots, m) \mid j \in J^+ \right\rangle, \right. \\
&\quad \left. \left\langle \max(x'_{ij} \mid i = 1, 2, \dots, m) \mid j \in J^- \right\rangle \right\} = \{x_j^- \mid j \\
&\quad = 1, 2, \dots, k\},
\end{aligned} \tag{6}$$

where the following equations apply:

$$\begin{aligned}
J^+ &= \{j = 1, 2, \dots, k \mid \\
&\quad j \text{ is associated with the criteria having a positive impact}\}, \\
J^- &= \{j = 1, 2, \dots, k \mid \\
&\quad j \text{ is associated with the criteria having a negative impact}\}.
\end{aligned} \tag{7}$$

Step 4 (setting trade-off relations among TC(sub)). In the system, the trade-off relations are set at the level of TC(sub). One TC(master) (x_{ij}) comprises one TC(sub) (x'_{ij}) as a default value. However, if TC(master) (x_{ij}) is a self-contradiction scale in the trade-off, TC(sub) will be defined as two different TC(sub) ($x'_{ij}, x'_{i(j+1)}$). Furthermore, TC(sub) ($x'_{ij}, x'_{i(j+1)}$) have opposite values for $\max(x'_{ij})$ and $\min(x'_{i(j+1)})$ from (2).

In another case, where one pair of TC(sub) has a trade-off relation, each TC(sub) value is defined by the relevant correlation function given by (1)–(3). The pair of trade-off TC(sub) can be represented using (8).

If TC(sub) (x'_{ij}) and TC(sub) ($x'_{ij'}$) are one pair of a trade-off relation,

$$\begin{aligned}
&\text{TC(sub)}(x'_{ij}) \\
&\ni x'_{ij} \text{ (positive ideal value} = \max(x'_{ij})), \\
&x'_{ij'} \text{ (negative ideal value} = \min(x'_{ij'})), \\
&\quad |j - j'| \leq k - 1 \\
&\text{TC(sub)}(x'_{ij'}) \\
&\ni x'_{ij'} \text{ (positive ideal value} = \max(x'_{ij'})),
\end{aligned}$$

$$\begin{aligned}
&x'_{ij'} \text{ (negative ideal value} = \min(x'_{ij'})), \\
&\quad |j - j'| \leq k - 1,
\end{aligned} \tag{8}$$

$$\begin{aligned}
&\text{TC(sub)}(x'_{ij'}) = a - b * \exp(c * \text{TC(sub)}(x'_{ij})), \\
&\text{monotone increasing,} \\
&\text{TC(sub)}(x'_{ij'}) = a - b * (\text{TC(sub)}(x'_{ij})), \quad b = 1, \\
&\text{inverse proportion,} \\
&\text{TC(sub)}(x'_{ij'}) = a + b * \exp(c * \text{TC(sub)}(x'_{ij})), \\
&\text{monotone decreasing.}
\end{aligned}$$

Here, a and b are positive constants such that “ $y(x)$ is 0 or a positive constant.” Further, c is a positive constant such that $0 < c < 1$.

Step 5 (normalizing TC(sub)). To normalize TC(sub) for the composition of different scales, a linear normalization method is used. The linear normalization is expressed as

$$r_{ij} = 1 - \frac{\max(x'_{ij}) - x'_{ij}}{\max(x'_{ij}) - \min(x'_{ij})}. \tag{9}$$

The cross-matrix R of the normalized element (r_{ij}) is given by

$$\begin{aligned}
&R = \begin{matrix} & \begin{matrix} X'_1 & X'_2 & \cdots & X'_k \end{matrix} \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ \vdots \\ A_m \end{matrix} & \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1k} \\ r_{21} & r_{22} & \cdots & r_{2k} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mk} \end{bmatrix} \end{matrix} \\
&(A_i : i = 1, 2, \dots, m \text{ and } g, l \text{ and } r_{ij} : j = 1, 2, \dots, k)
\end{aligned} \tag{10}$$

$$\begin{matrix} A_g \\ A_l \end{matrix} \begin{bmatrix} r_{g1} & r_{g2} & \cdots & r_{gk} \\ r_{l1} & r_{l2} & \cdots & r_{lk} \end{bmatrix}.$$

Step 6 (applying weights to the normalized matrix R). The weights are defined as w_j ($j = 1, 2, \dots, k$). The values of the weights lie between 0 and 10. The matrix V for applying the weights to the cross-matrix R is given by the following equation:

$$\begin{aligned}
V &= \begin{matrix} & \begin{matrix} X'_1 & X'_2 & \cdots & X'_k \end{matrix} \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ \vdots \\ A_m \end{matrix} & \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \cdots & w_k r_{1k} \\ w_1 r_{21} & w_2 r_{22} & \cdots & w_k r_{2k} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ w_1 r_{m1} & w_2 r_{m2} & \cdots & w_k r_{mk} \end{bmatrix} \end{matrix} = \begin{matrix} & \begin{matrix} X'_1 & X'_2 & \cdots & X'_k \end{matrix} \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ \vdots \\ A_m \end{matrix} & \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1k} \\ v_{21} & v_{22} & \cdots & v_{2k} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mk} \end{bmatrix} \end{matrix} \\
&\begin{matrix} A_g \\ A_l \end{matrix} \begin{bmatrix} w_1 r_{g1} & w_2 r_{g2} & \cdots & w_k r_{gk} \\ w_1 r_{l1} & w_2 r_{l2} & \cdots & w_k r_{lk} \end{bmatrix} = \begin{matrix} & \begin{matrix} X'_1 & X'_2 & \cdots & X'_k \end{matrix} \\ \begin{matrix} A_g \\ A_l \end{matrix} & \begin{bmatrix} v_{g1} & v_{g2} & \cdots & v_{gk} \\ v_{l1} & v_{l2} & \cdots & v_{lk} \end{bmatrix}.
\end{aligned} \tag{11}$$

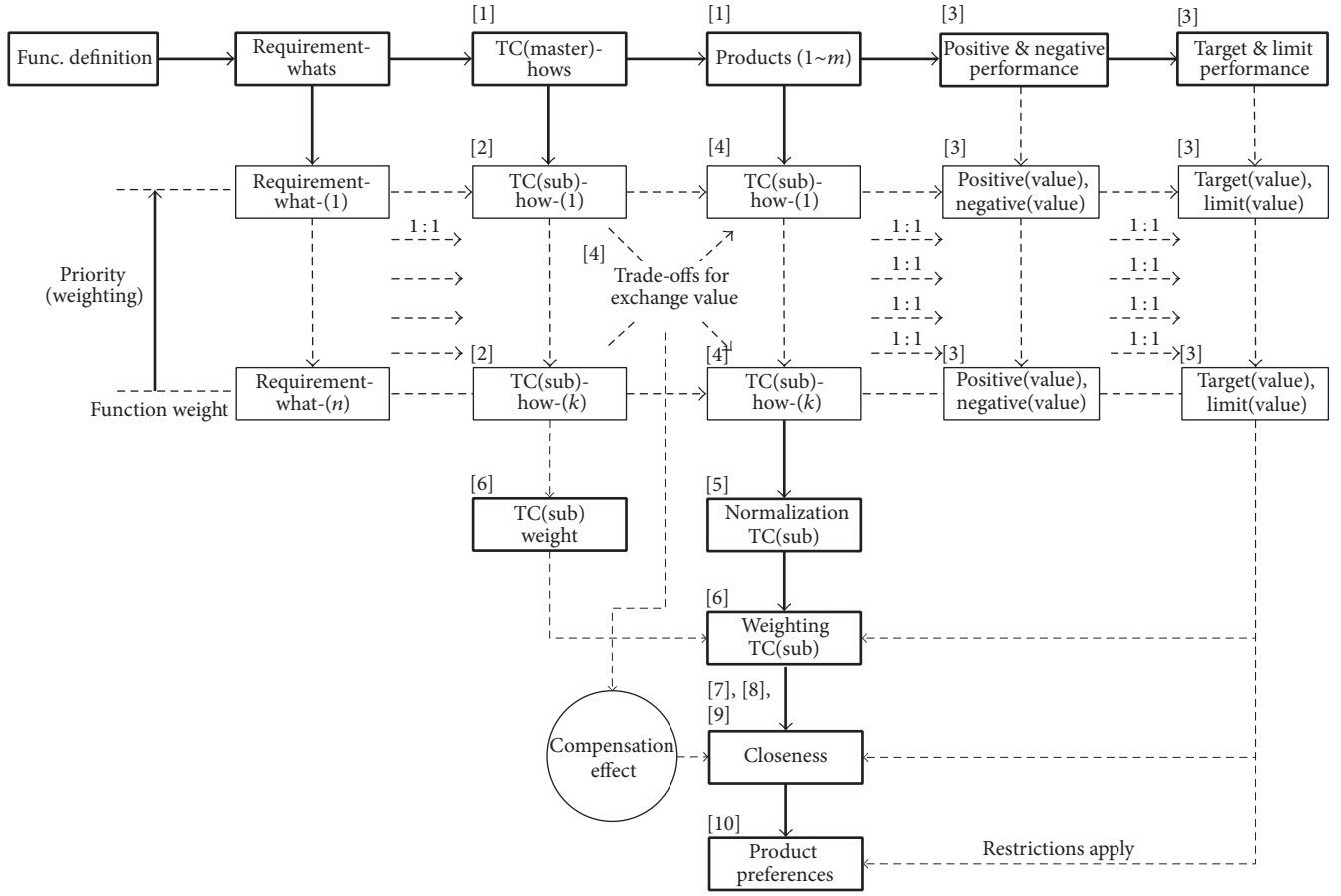


FIGURE 6: Advanced QFD-TOPSIS model from the QFD matrix.

Step 7 (calculating the maximum value of v_{ik}). The maximum value, $A_{(\max)}$, is defined as

$$A_{(\max)} = \{\max(v_j); j = 1, 2, \dots, k\} \\ = \{v_1^+, v_2^+, \dots, v_k^+\}, \quad (12)$$

where $A_{(\max)}$ denotes the ideal technical characteristics with the highest preference.

Step 8 (calculating the internal measure). The distance from the ideal solution, $A_{(\max)}$, for each product is calculated as

$$S_i^+ = \left[\sum_{j=1}^k (v_{ij} - v_j^+)^2 \right]^{1/2} \quad (i = 1, 2, \dots, m \text{ and } g, l). \quad (13)$$

The separation from the negative solution, A^- , for each product is calculated as

$$S_i^- = \sum_{j=1}^k v_{ij} \quad (i = 1, 2, \dots, m \text{ and } g, l). \quad (14)$$

Step 9 (calculating relative closeness from the ideal solution). The relative closeness C_i of A_i with respect to the ideal solution $A_{(\max)}$ is defined as

$$C_i = \frac{S_i^-}{(S_i^+ + S_i^-)} \quad (15)$$

$$(0 < C_i < 1), \quad (i = 1, 2, \dots, m \text{ and } g, l).$$

As C_i approaches 1, A_i approaches $A_{(\max)}$.

Step 10 (aligning products based on the preference value C_i). The order of preference for the products is determined by the size of C_i . In addition, any product consistent with the threshold of a TC(sub) is considered an unsuitable alternative and excluded from the alternatives for selection.

Figure 6 shows the conceptual process of QFD-TOPSIS that is developed from the original QFD.

5. Verification of QFD-TOPSIS System

In this section, we present a unified modeling language (UML) model and a test operation for the QFD-TOPSIS system.

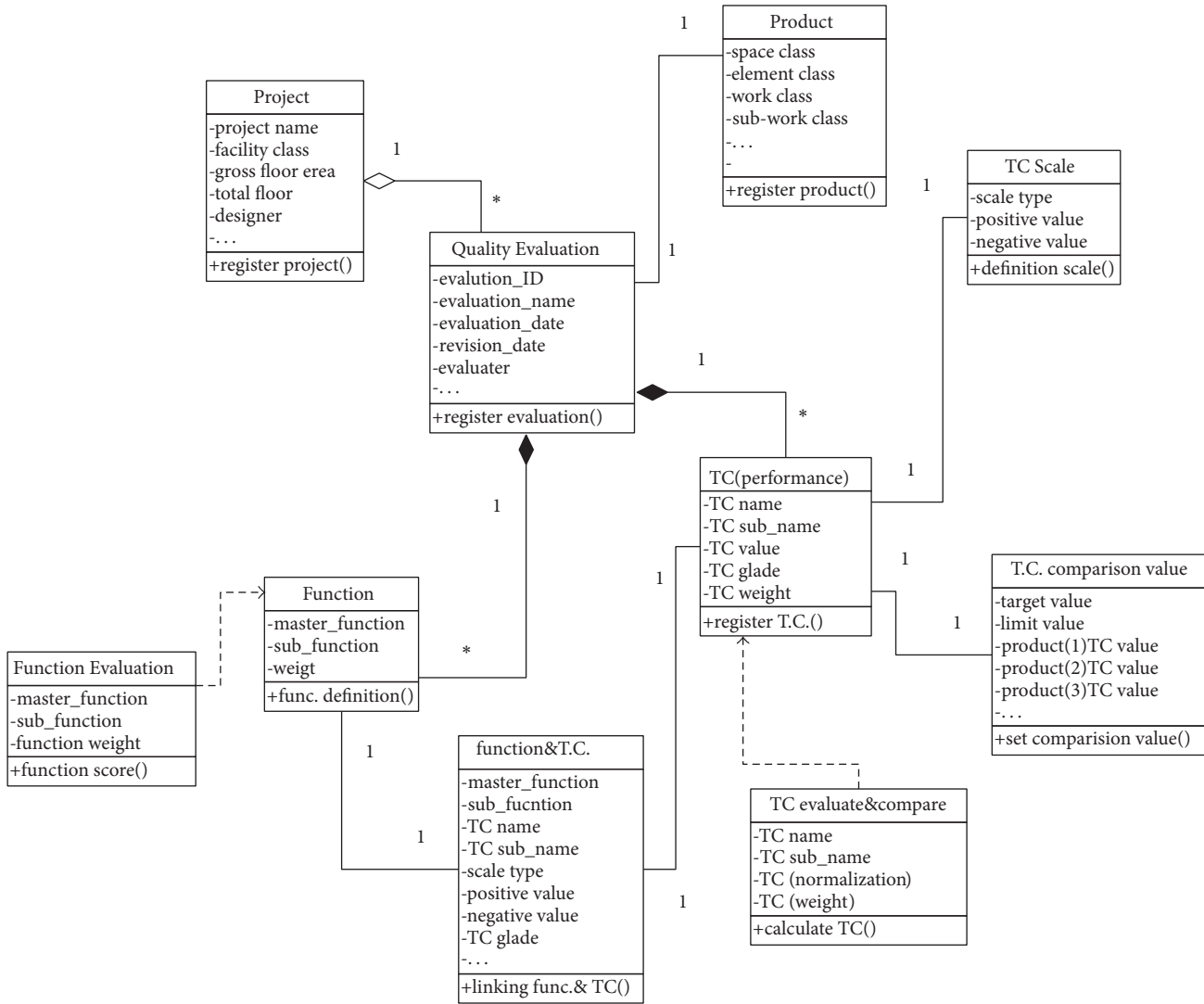


FIGURE 7: UML diagram for a QFD-TOPSIS Web-based quality evaluation system.

The users of this system include facility managers, clients, designers, engineers, contractors, and manufacturers. A single facility project may consist of multiple products or elements, while an evaluation by multiple appraisers (users, designers, engineers, contractors, etc.) applies to one product (one design solution). Moreover, the evaluation can be revised repeatedly by one or multiple appraisers (appraising team).

As shown in the UML diagram (Figure 7), the Function Evaluation class represents the dependency relationship of the function class, and the TC evaluate and compare class represents the dependency relationship of the TC(performance) class.

The quality evaluation system establishes a 1:1 relationship between the required functions and the TC. In turn, multiple alternatives are intercompared with regard to the function and TC in consideration of the limit or target value.

In the case study, the test data from “QFD Based Benchmarking Logic Using TOPSIS and Suitability Index” [16]

was used. The test data comprises the performance values of window products for a building. The “target performance” and “limit performance” of the window products in terms of the building are arbitrarily set by the users.

The performance items consist of the following: *U*-value (glazing): interval scale, *U*-value (total): interval scale, SHGC (summer): interval scale, SHGC (winter): interval scale, VT: 5-grade scale, CR: 4-grade scale, AT: 3-grade scale, WS: binary scale, and WT: binary scale.

The *U*-value measures the amount of heat that is transferred through the window. A lower *U*-value indicates better thermal insulation performance. The *U*-value can be classified by the glass itself and the glass curtain wall including the frame.

The solar heat gain coefficient (SHGC) measures the amount of solar radiation that passes through the window. SHGC is expressed as a number between 0 and 1. The lower the SHGC of a window, the smaller the amount of solar heat that it transmits. In terms of the users’ functional

Home > (phase) Function Definition Management > Function & Characteristic(sub) Link

Assessment ID :QA00000002		Evaluation Name : Building Window System					
				Search Item	Assessment ID ▾	Contents	<input type="button" value="Search"/>
number	function (master)	number(sub)	function(sub)	characteristics (sub)	ideally value	negative value	Characteristic Link
1	Thermal Environment	1	Heat insulating function of the outer heat transfer	U-Value (Cladding)	0.00	1.00	Characteristic Link
2	Thermal Environment	2	Insulating windows for the entire frame	U-Value(Total)	0.00	1.00	Characteristic Link
3	Thermal Environment	3	The summer cooling load caused by solar radiation minimized	SHGC(Summer)	0.10	0.60	Characteristic Link
4	Thermal Environment	4	The winter warming load caused by solar radiation minimized	SHGC(Winter)	0.60	0.10	Characteristic Link
5	Functional	1	Visibility for field view and minimize brightness	VT	grade 1	grade 5	Characteristic Link
6	Functional	2	Anti-condensation caused by the temperature difference inside and outside	CR	grade 1	grade 4	Characteristic Link
7	Functional	3	Air leakage barrier	AT	grade 1	grade 3	Characteristic Link
8	durability	1	Structural stability of the wind	WS	T	F	Characteristic Link
9	durability	2	Structural durability of the water	WT	F	T	Characteristic Link

FIGURE 8: Linking of the functions and TC(sub).

requirements, SHGC can be classified into SHGC (summer) and SHGC (winter). The ideal values for SHGC (summer) and SHGC (winter) are 1 and 0, respectively.

Visible transmittance (VT) is the amount of light in the visible portion of the spectrum that passes through a glazing material. A higher VT grade indicates a greater amount of daylight in a space. When the space is designed, the electric lighting and its associated cooling loads should be offset. VT is expressed on a five-grade scale, where grade 1 represents the highest VT performance.

Condensation resistance (CR) measures a product's resistance against condensation formation. CR is expressed on a four-grade scale, where grade 1 represents the best CR performance.

Air-tightness (AT) can be defined as the resistance to inward or outward air leakage that occurs through unintentional leakage points or areas of the building envelope. AT is expressed on a three-grade scale, where grade 1 represents the best AT performance.

Wind safety (WS) indicates the safety of a window against wind; the safety measurement follows the standards of the ASTM E330 test. In this case study, a binary scale was adopted for WS.

Water tightness (WT) indicates the window's resistance against water leakage. The amount of water leakage must be 0 based on the standards of the ASTM E 331 test. In this case study, the WT was evaluated as 1 ("no leakage" as suitable) or 0 ("leakage" as unsuitable).

A screenshot of the definitions of the 1:1 relationship between the functions and TC(sub) is shown in Figure 8.

A comparison of the normalized TC values is shown in Figure 9.

The weighting TC values and a comparison of the windows are shown in Figure 10.

The completion of the cross-matrix of QFD-TOPSIS is shown in Figure 11. As subclassifications of SHGC, TC "SHGC (summer)" and "SHGC (winter)" are self-contradictory trade-off TC, which are specified in the cross-matrix. At the bottom of the cross-matrix, six market product preferences involved in the trade-off effect are listed. In addition, the target product and limit product preferences are listed. The (c) and (d) among the 6 products are excluded due to the restrictive condition.

Home > (phase) Output Management > Comparison Characteristic(sub)

Assessment ID :QA00000002		Evaluation Name : Building Window System												
Excel Download														
number	characteristic name	characteristics (sub)	scale type	scale property	weight	substitutability weight	Product(A)	Product(B)	Product(C)	Product(D)	Product(E)	Product(F)	Target	Limit
1	U-Value	U-Value(Cladding)	distance scale	single criteria	10.00	10.00	0.70	0.82	0.86	0.75	0.84	0.70	0.80	0.60
2	U-Value	U-Value(Total)	distance scale	single criteria	10.00	10.00	0.75	0.80	0.83	0.71	0.80	0.65	0.70	0.60
3	SHGC	SHGC(Summer)	distance scale	trade-off	8.00	8.00	0.64	0.50	0.32	0.24	0.40	0.60	0.80	0.40
4	SHGC	SHGC(Winter)	distance scale	trade-off	8.00	8.00	0.36	0.50	0.68	0.76	0.60	0.40	0.60	0.20
5	VT	VT	grade 5	single criteria	5.00	5.00	0.50	0.50	0.50	0.75	0.50	0.25	0.50	0.25
6	CR	CR	grade 4	single criteria	5.00	5.00	0.67	1.00	0.67	0.67	0.67	0.33	0.67	0.33
7	AT	AT	grade 3	single criteria	7.00	7.00	1.00	0.50	0.50	0.00	1.00	0.50	1.00	0.50
8	WS	WS	T/F	single criteria	7.00	7.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00
9	WT	WT	T/F	single criteria	7.00	7.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00

FIGURE 9: Comparison of the normalized TC values.

Home > (phase) Output Management > Comparison Functions Score

Assessment ID :QA00000002 Evaluation Name : Building Window System												
Excel Download												
number	function (master)	function (sub)	weight	characteristics (sub)	Product(A)	Product(B)	Product(C)	Product(D)	Product(E)	Product(F)	Target	Limit
1	Thermal Environment	Heat insulating function of the outer test window	10.00	U-Value(Cladding)	7.00	8.20	8.60	7.50	8.40	7.00	8.00	6.00
2	Thermal Environment	Insulating windows for the entire frame	10.00	U-Value(Total)	7.50	8.00	8.30	7.10	8.00	6.50	7.00	6.00
3	Thermal Environment	The summer cooling load caused by solar radiation minimized	8.00	SHGC(Summer)	5.12	4.00	2.56	1.92	3.20	4.80	6.40	3.20
4	Thermal Environment	The winter warming load caused by solar radiation minimized	8.00	SHGC(Winter)	2.88	4.00	3.44	6.08	4.80	3.20	4.80	1.60
5	Functional	Visibility for field view and minimize brightness	5.00	VT	2.50	2.50	2.50	3.75	2.50	1.25	2.50	1.25
6	Functional	Anti-condensation caused by the temperature difference inside and outside	5.00	CR	3.35	5.00	3.35	3.35	3.35	1.65	3.35	1.65
7	Functional	Air leakage barrier	7.00	AT	7.00	3.50	3.50	0.00	7.00	3.50	7.00	3.50
8	durability	Structural stability of the wind	7.00	WS	7.00	7.00	0.00	7.00	7.00	7.00	7.00	7.00
9	durability	Structural durability of the water	7.00	WT	7.00	7.00	0.00	7.00	7.00	7.00	7.00	7.00

FIGURE 10: Comparison of the weighted TC values.

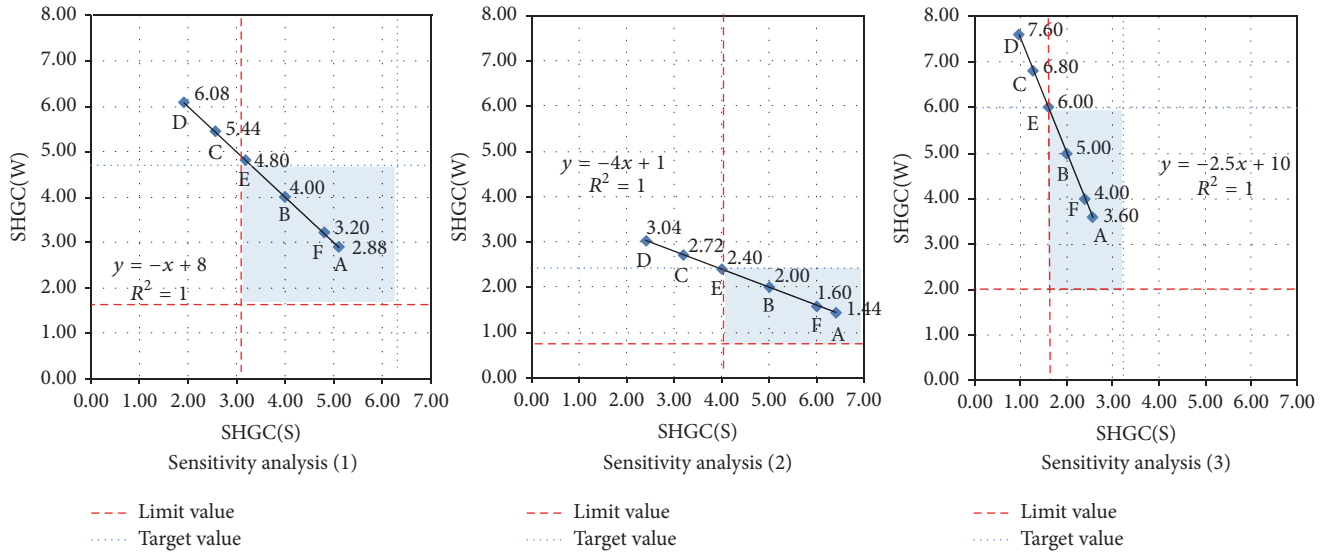
QFD-TOPSIS Matrix
Assessment ID : 0000001 Evaluation Name : Building Window System

Items		Definition of TC(sub) and function									
TC(master)	TC(sub)	weight	priority	scale	position	negative	target	limit	Function description		
U-Value	U-Value(Cladding)	10	1	internal scale	0	1	0.20	0.40	Heat insulating function of the outer heat transfer		
U-Value	U-Value(Total)	10	1	internal scale	0	1	0.30	0.40	Insulating windows for the entire frame		
SHGC	SHGC(Summer)	8	2	internal scale	0.1	0.6	0.20	0.40	The summer cooling load caused by solar radiation minimized		
SHGC	SHGC(Winter)	8	2	internal scale	0.6	0.1	0.40	0.20	The winter warming load caused by solar radiation minimized		
VT	VT	5	4	grade 5	grade 1	grade 5	grade 3	grade 4	Visibility for field view and minimize brightness		
CR	CR	5	4	grade 4	grade 4	grade 2	grade 3	grade 3	Anti-condensation caused by the temperature difference inside and outside		
AT	AT	7	3	grade 3	grade 3	grade 3	grade 1	grade 2	Air leakage barrier		
WS	WS	7	3	T/F	T	F	T	T	Structural stability of the wind		
WT	WT	7	3	T/F	F	T	F	F	Structural durability of the water		

Items		TC(sub) Relationship									
TC(master)	TC(sub)	U-Value	U-Value	SHGC	SHGC	VT	CR	AT	WS	WT	Correlation Function
U-Value	U-Value(Cladding)	●									-
U-Value	U-Value(Total)		●								-
SHGC	SHGC(Summer)			●							-
SHGC	SHGC(Winter)				●						-
VT	VT					●					-
CR	CR						●				-
AT	AT							●			-
WS	WS								●		-
WT	WT									●	-

Items		Products preference and suitability											
TC(master)	U-Value	U-Value	SHGC	SHGC	VT	CR	AT	WS	WT	Normalization value	Preference	Restrictions filter	
TC(sub)	U-Value (cladding)	U-Value (Total)	SHGC (Summer)	SHGC (Winter)	VT	CR	AT	WS	WT				
TC(sub) Weight	10	10	8	8	5	5	7	7	7				
Product(A)	1.00	0.70	0.75	0.64	0.38	0.50	0.67	1.00	1.00	1.00	0.74	0.74	suitable
Product(B)	1.00	0.82	0.80	0.50	0.50	0.50	1.00	0.50	1.00	1.00	0.74	0.73	suitable
Product(C)	0.60	0.60	0.60	0.81	0.44	0.30	0.67	0.50	0.50	0.50	0.48	0.51	unsuitable
Product(D)	0.75	0.75	0.71	0.76	0.75	0.33	0.67	0.60	1.00	1.00	0.65	0.65	unsuitable
Product(E)	0.64	0.64	0.60	0.60	0.60	0.50	0.67	0.50	1.00	1.00	0.76	0.76	suitable
Product(F)	0.70	0.70	0.65	0.60	0.40	0.25	0.33	0.50	1.00	1.00	0.60	0.60	suitable
Target value	0.80	0.80	0.70	0.80	0.60	0.50	0.67	1.00	1.00	1.00	0.79	0.79	suitable
Limit value	0.60	0.60	0.60	0.60	0.25	0.25	0.33	0.50	1.00	1.00	0.54	0.56	suitable

FIGURE 11: Denotation of trade-off TC(sub) and preferences for the market products.



Self-contradiction trade-offs

Sensitive analysis (1)	Product(A)	Product(B)	Product(C)	Product(D)	Product(E)	Product(F)	Target	Limit	Weight
SHGC(S) advantage	5.12	4.00	2.56	1.92	3.20	4.80	6.40	3.20	8
SHGC(W) advantage	2.88	4.00	5.44	6.08	4.80	3.20	4.80	1.60	8

Self-contradiction trade-offs

Sensitive analysis (2)	Product(A)	Product(B)	Product(C)	Product(D)	Product(E)	Product(F)	Target	Limit	Weight
SHGC(S) advantage	6.40	5.00	3.20	2.40	4.00	6.00	8.00	4.00	10
SHGC(W) advantage	1.44	2.00	2.72	3.04	2.40	1.60	2.40	0.80	4

Self-contradiction trade-offs

Sensitive analysis (3)	Product(A)	Product(B)	Product(C)	Product(D)	Product(E)	Product(F)	Target	Limit	Weight
SHGC(S) advantage	2.56	2.00	1.28	0.96	1.60	2.40	3.20	1.60	4
SHGC(W) advantage	3.60	5.00	6.80	7.60	6.00	4.00	6.00	2.00	10

Product preference

Preference	Product(A)	Product(B)	Product(C)	Product(D)	Product(E)	Product(F)
Sensitive analysis (1)	0.74	0.73	0.51	0.65	0.76	0.63
Sensitive analysis (2)	0.76	0.74	0.49	0.63	0.76	0.64
Sensitive analysis (3)	0.73	0.74	0.53	0.68	0.78	0.62

Product preference rank

Preference	Product(A)	Product(B)	Product(C)	Product(D)	Product(E)	Product(F)
Sensitive analysis (1)	2	3	6	4	1	5
Sensitive analysis (2)	1	2	5	4	1	3
Sensitive analysis (3)	3	2	6	4	1	5

FIGURE 12: Sensitivity analysis of changes in the trade-off TC(sub) weights.

6. Sensitivity Analysis

Here, SHGC(S) and SHGC(W) are defined as “self-contradictory trade-off TC(sub).” The sensitivity analysis of the trade-off TC(sub) to alterations of the users’ weights is shown in Figure 12

In “sensitivity analysis (2),” the weights for SHGC(S) and SHGC(W) were changed to 10 and 4, respectively, owing to the regional characteristic of the temperate climate. In “sensitivity analysis (3),” the weights for SHGC(S) and SHGC(W) were changed to 4 and 10, respectively, owing to the regional characteristic of the microthermal climate.

Based on the results obtained from the sensitivity analyses, different outcomes were observed with respect to the compensation effect, which is a monotonic decrease in the trade-off TC(sub) relation. It was confirmed that the trade-off TC(sub) value is dependent on the definitions of the user weights. In addition, the overall product preferences for the alternative products changed with the trade-off TC(sub) weights. The subpreference ranks are shown in Figure 12.

7. Conclusions

This paper proposed a new advanced QFD-TOPSIS logic and the corresponding system for solving MCDM problems with regard to trade-off. The complex relationship and the subjective result of HOQ have hindered QFD from industrial application. Therefore, the present study combined TOPSIS with QFD to address the challenge.

The QFD-TOPSIS model is free of complex relationships between functions and TC through the simple 1:1 relations. The QFD-TOPSIS model can also clearly express the trade-off between TC that can be described by a mathematical correlation function. The QFD-TOPSIS logic not only measures the relative loss arising from trade-off TC, but also automatically analyzes the suitability of a product based on the predefined threshold of TC.

It also allows the QFD-TOPSIS system to compare multiple market products with the use of positive/negative ideal criteria and target and limit values. Finally, the model presents the preferred design solution made by considering user weights in the trade-off problem where the user needs to define priority TC for proper decision-making.

This test operation validated the MCDM solutions to address the objective and subjective comparison of construction product TC in a Web-based system. The case was conducted based on self-contradictory trade-off TC.

Additional tests, especially in the case of a pair of trade-off TC in other disciplines, are required to explore the preferences for employing the correlation functions of TC values. Further investigation is also required to extend the findings of this study to other fields, such as product suitability, safety analysis, and automatic quality check, where the requirements and standard criteria should be applied.

Disclosure

Jaeho Cho is the first author.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research was supported by a grant (15AUDP-C067809-03) from Architecture & Urban Development Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government. And this research was

supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2015R1D1A1A01060356).

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