Quality Function Deployment Using Improved Interpretive Structural Modeling

Takeo Kato[1] and Yoshiyuki Matsuoka[2]

[1] Department of Mechanical Engineering,
Tokai University, Japan
t.kato@tokai-u.jp
[2] Department of Mechanical Engineering,
Keio University, Japan
matsuoka@mech.keio.ac.jp

Abstract. Due to the product diversification and complication, sharing the product information between the product development members has been important in the product development process. Quality Function Deployment (QFD) is one of the effective methods to share the information of the product using the quality matrices that describes the relationship between design elements needed to be considered. This paper improves QFD by applying the Interpretive structural modeling (ISM). The ISM visually expresses the complex relationship between design elements by using matrix operation. This paper also improves the ISM in order to evaluate not only the relationships between the same type of design elements but also that between in different type. The proposed QFD is applied to a disc brake design problem, and their applicability is confirmed.

Keywords: Design Methodology, QFD, ISM, Structural Modeling.

1 Introduction

The functions and mechanisms of products have diversified and have become increasingly complicated, resulting in the specialization and professionalization of design work [1]. Consequently, it is difficult for members of a product design team to share product information. This lack of information between design team members is a significant issue for manufacturing companies because it leads to design changes or quality issues in the design process.

Quality Function Deployment (QFD) [2, 3] is an effective method to resolve the above problem. Using quality charts, design elements of customer demands (considered in the early process of design) can be translated into those of the quality characteristics, product function, parts, etc. (considered in the latter process of design). Deployment charts, including allied design elements, are used to prepare quality charts, and relationship matrices depict the relationship between design elements in the different deployment charts.

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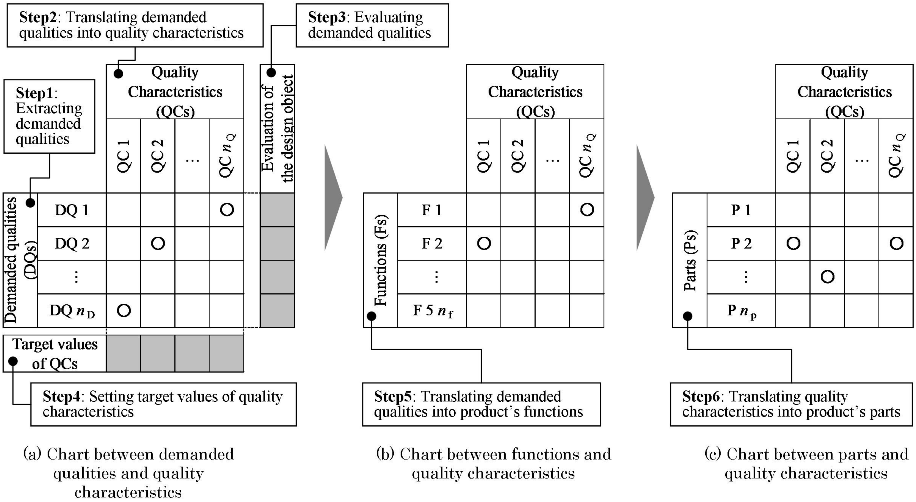
The conventional QFD was proposed in 1976 and contains several quality charts:

1. One expresses the relationships between demanded qualities and quality characteristics that are transformed from the demanded qualities in order to be evaluated quantitatively (Fig. 1a);
2. One depicts the relationships between quality characteristics and functions of the product extracted from the demanded qualities (Fig. 1b);
3. One depicts the relationships between quality characteristics and product parts (Fig. 1c).



(a) Chart between demanded qualities and quality characteristics

(b) Chart between functions and quality characteristics

(c) Chart between parts and quality characteristics

Fig. 1. Conceptual diagram of quality matrices used in QFD

These quality charts enable designers to clarify the design elements of all design processes (from the demanded qualities to the product parts) and their relationships. Based on the conventional QFD, diverse QFDs have been proposed. Although most QFDs contain quality charts, their design object or objective differs. Research on QFDs can be classified as: (i) improved methods to evaluate the design elements, (ii) change in the items of the quality charts, (iii) usage assistance, and (iv) other applications of QFD.

Many groups have strived to improve the evaluation method. Kuo [4] and Chen [5] proposed a method using a fuzzy approach to reduce the vagueness and uncertainty in the decision-making with respect to the target of the demanded qualities or quality characteristics. Bode [6] calculated the product quality from the strength of the relationship between design elements shown in QFD, and suggested an optimization method to maximize QFD under a cost constraint. Hsiao [7] integrated QFD, FMEA, DFA (Design for Assembly), and AHP (Analytic Hierarchy Process) to evaluate the total quality of the product.

With respect to research to change items in the quality charts, Barad [8] proposed quality charts with the departments and tasks of the company to optimize task implementation.

Zhang [9] and Masui [10] evaluated the environment requirements using QFD. Zhang constructed GQFD (Green QFD) to conduct the LCA (Life Cycle Assessment) and LCC (Life Cycle Costing), while Masui suggested QFDE (QFD for environment) to handle the environmental and traditional product quality requirements simultaneously. Ashihara [11] applied the TSC (Technology Sensitivity Chart), which represents the relationship between new technologies and prospective demanded qualities, and proposed the inverse of QFD to clarify the objectives of product design and technology research.

With the aid in usage, Yeh [12] suggested that QFD and TRIZ be integrated to remove the bottleneck due to clarifying QFD. Huang [13] uploaded QFD onto a Web server, which enabled design members to share real-time information. Matsuoka [14] and Miwa [15] clarified the design process and modular parts based on the relationships of the design elements using ISM (Interpretive Structural Modeling) and DSM (Design Structure Matrix), respectively.

Similar to the aims of Matsuoka [14] or Miwa [15], this study strives to improve QFD in order to aid user comprehension of the complicated relationships between design elements. To calculate information from deployment charts and relationship matrices, herein ISM applied to QFD (Matsuoka [14]) is improved. This improvement allows QFD users (e.g., product planners, product designers, and engineering designers) to easily understand both the relationships between the same type of design elements and those between different types.

This paper is organized as follows. Section 2 explains the rationale for selecting ISM and applies it to QFD. Section 3 overviews the proposed QFD using the improved ISM. Section 4 applies the proposed QFD to a disc brake, while Section 5 provides conclusions and the future research direction.

2 Interpretive Structural Modeling

DSM, which is one of the most effective methods to clarify the relationship between design elements, has been applied to the QFD [14]. Additionally, DMM (Domain Mapping Matrices), which expresses the relationship of the elements in different domains (types), can be used with DSM. Similar to DMM, QFD includes multiple elements. Specifically, QFD contains three domains of design elements: functions, quality characteristics, and parts. Thus, applying DSM to QFD may be effective.

However, methods like DSM, which express relationships in matrices, have some drawbacks. 1) Compared to methods using graphical expressions (connecting the relative elements with a line), users cannot intuitively comprehend the relationship. 2) The alignment of the matrix cannot obtain more than two objectives [16]. For example, DSM cannot be simultaneously aligned for both grouping (referred to as "clustering" in the DSM) and stratifying (referred to as "partitioning").

In the field of mass customization strategies, customers can select the specifications (parts) of the merchandise. Suzić [17] employed FFA (Factory Flow Analysis) and determined the proper location of working machines in the factory line without returning flow in the production process. In FFA, parts manufactured by machines are grouped using a matrix between the working machines and parts. Then the parts are stratified by a material flow diagram (graphical expression). Because this method only considers the relationships between parts and machines, it is difficult to apply FFA to QFD, which must consider the internal and external relationships of the functions, quality characteristics, and part elements.

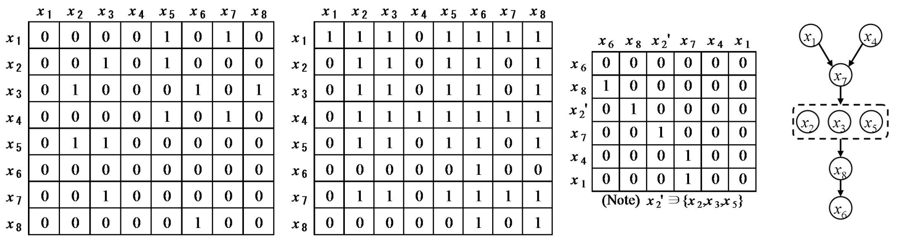
These conventional methods have advantages and disadvantages with respect to procedures for grouping and stratifying, graphical expressions, and inter-domain relationships evaluation. This study aims to improve the comprehension of complicated relationships and to overcome the disadvantages using ISM.

ISM is a design method to visually express complex relationships between design elements via matrix operations [18]. In ISM, direct affective matrix **X** (Fig. 2a), which expresses the relationship between design elements, is initially constructed according to the following equation:

$$\mathbf{X} = \begin{pmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & & & & \\ x_{i1} & & \ddots & & \vdots \\ \vdots & & & & \\ x_{n1} & & \cdots & & x_{nn} \end{pmatrix} \tag{1}$$

where n is the number of design elements. x_{ij} values are calculated as:

$$x_{ij} = \begin{cases} 1 & \text{if } i \text{ the element relates to } j \text{ th element} \\ 0 & \text{else} \end{cases} \tag{2}$$
$$(i = 1, 2, \cdots, n \quad , \quad j = 1, 2, \cdots, n) \quad .$$



	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
x_1	0	0	0	0	1	0	1	0
x_2	0	0	1	0	1	0	0	0
x_3	0	1	0	0	0	1	0	1
x_4	0	0	0	0	1	0	1	0
x_5	0	1	1	0	0	0	0	0
x_6	0	0	0	0	0	0	0	0
x_7	0	0	1	0	0	0	0	0
x_8	0	0	0	0	0	1	0	0

(a) Direct affective matrix

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
x_1	1	1	1	0	1	1	1	1
x_2	0	1	1	0	1	1	0	1
x_3	0	1	1	0	1	1	0	1
x_4	0	1	1	1	1	1	1	1
x_5	0	1	1	0	1	1	0	1
x_6	0	0	0	0	0	1	0	0
x_7	0	1	1	0	1	1	1	1
x_8	0	0	0	0	0	1	0	1

(b) Reachable matrix

	x_6	x_8	x_2'	x_7	x_4	x_1
x_6	0	0	0	0	0	0
x_8	1	0	0	0	0	0
x_2'	0	1	0	0	0	0
x_7	0	0	1	0	0	0
x_4	0	0	0	1	0	0
x_1	0	0	0	1	0	0

(Note) $x_2' \ni \{x_2, x_3, x_5\}$

(c) Skeleton matrix

(d) Structural model

Fig. 2. Conceptual diagram of ISM (x_1 - x_8 are design elements)

Secondly, reachable matrix $\mathbf{M}_\mathrm{R}$ (Fig. 2b) is derived using matrix **M**, which is calculated by adding direct affective matrix **X** and the unit matrix (i.e., **M** = **X** + **I**), as shown in the following equation:

$$\mathbf{M}_\mathrm{R} = \mathbf{M}^r \qquad \left(\mathbf{M}^r = \mathbf{M}^{r-1}\right) \tag{3}$$

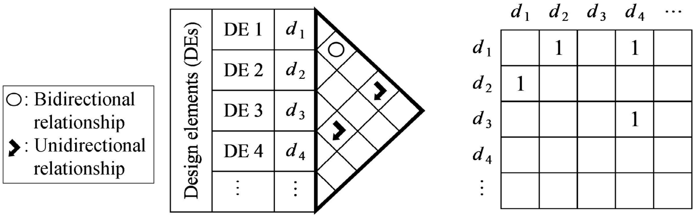
Finally, reachable matrix $\mathbf{M}_\mathrm{R}$ is transformed into skeleton matrix $\mathbf{M}_\mathrm{S}$ (Fig. 2c), and the structural model (Fig. 2d) is constructed based on the relationship in the matrix.

The skeleton matrix can represent the relationship of the reachable matrix using minimum relationships. This paper omits the detailed calculation of the skeleton matrix because it has already been reported [18]. This matrix has two main features: 1) elements affecting each other are grouped and 2) the higher an element is located, the more elements it can affect. Thus, ISM can simultaneously group and stratify. Additionally, ISM can provide a structural model (graphical expressing).

3 Proposed QFD Using ISM

3.1 Improvement of ISM

To apply ISM, this study introduces a correlation matrix into each of the three deployment charts in QFD. Figure 3a shows an example of a correlation matrix regarding parts. In the matrix, unidirectional relationships (i.e., element "A" relates to "B" but "B" does not relate to "A") are described by arrows, whereas bidirectional relationships (i.e., element "A" relates to "B" and "B" relates to "A") are described by circles. In Fig. 3a, design element 1 (d_1) affects both d_2 and d_n, and is affected by d_2. Figure 3b shows the direct affective matrix derived from the correlation matrix. The direct affective matrix improves the grouping and stratifying processes as well as graphical expressions in DSM, but the inter-domain relationships in FFA remain.



(a) Correlation matrix (b) Direct affective matrix

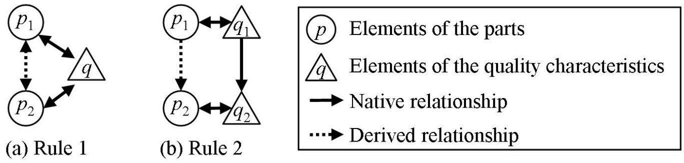
Fig. 3. Correlation matrix and direct affective matrix

Quality characteristic elements express the actual behaviors (features) of the product and connect the function and part elements. Therefore, understanding the relationships between quality characteristic elements is important to determine the trade-off between functions as well as to construct modules or the design process of parts. This study improves the direct affective matrix in order to comprehend the relationships between the three domains in QFD: functions, quality characteristics, and parts. Specifically, the relationships of the quality characteristics are added to both the function and part relationships.

The procedure below clarifies the part relationships while considering the quality characteristic relationships using ISM.

Because the procedure for the function relationships is the same as that for the part relationships, its description is abbreviated. To consider the quality characteristic relationships, the following two rules are added to construct a correlation matrix. 1)

Bidirectional relationships must be derived between part elements related to a common quality characteristic element (Fig. 4a). 2) Unidirectional relationships of the part elements in the same direction must be derived as the relationship of quality characteristic elements related to the part elements (Fig. 4b).



(a) Rule 1 (b) Rule 2

Fig. 4. Derived relationship of parts elements based on the quality characteristics relationship

The direct affective matrix of the parts based on the first rule $\mathbf{P}^{1)}$ can be expressed as:

$$\mathbf{P}^{1)} = p_{kl} = \begin{cases} 1 & \text{if } \sum_{i}^{n_\mathrm{q}} (p_k, q_i)\cdot(p_l, q_i) = 1 \\ 0 & \text{else} \end{cases} \tag{4}$$
$$\left(k = 1, 2, \cdots, n_\mathrm{p} \ , l = 1, 2, \cdots, n_\mathrm{p} , \ k \neq l\right)$$

where the calculation is based on Boolean operations. p_{kl} denotes the value of matrix $\mathbf{P}^{1)}$ in the k th row and l th column. q_{ij} is the value of a direct affective matrix of the quality characteristics in the i th row and j th column. (p_m, q_n) represents the value of the relation matrix between the quality characteristics and parts in the m th row and n th column. n_p and n_q denote the number of the parts and quality characteristics, respectively.

Similarly, the direct affective matrix with regard to the second rule $\mathbf{P}^{2)}$ is expressed as:

$$\mathbf{P}^{2)} = p_{kl} = \begin{cases} 1 & \text{if } (p_k, q_i)\cdot(p_l, q_j) = 1 \, \big| \, q_{ij} = 1 \\ 0 & \text{else} \end{cases} \tag{5}$$
$$\begin{pmatrix} i = 1, 2, \cdots, n_\mathrm{q} \ , \ j = 1, 2, \cdots, n_\mathrm{q} \ , i \neq j \\ k = 1, 2, \cdots, n_\mathrm{p} \ , \ l = 1, 2, \cdots, n_\mathrm{p} , \ k \neq l \end{pmatrix} .$$

By adding Equations 4 and 5 to the original direct affective matrix of part elements **P**, the direct affective matrix that considers quality characteristic relationships **P′** can be calculated as:

$$\mathbf{P}' = \mathbf{P} + \mathbf{P}^{1)} + \mathbf{P}^{2)} \tag{6}$$

3.2 Procedure of Proposed QFD

Figure 5 shows the proposed quality matrices, which include three deployment charts (function, quality characteristics, and parts), two relationship matrices, and three correlation matrices. The procedure of the proposed quality matrices is as follows. Step 1 extracts the design elements, including quality characteristics and parts. Step 2 develops the relationship matrices between the extracted elements. Step 3 constructs the correlation matrices. Steps 1–3 are repeated until the product development members are satisfied. Then Step 4 develops the direct affective matrix of the parts based on the correlation and relationship matrices of the quality characteristics and parts using Eq. 6. Similarly, the direct affective matrix of functions is constructed. Finally, Step 5 constructs the structural models of the elements via ISM using the direct affective matrices. Based on the structural models, the designers can proceed with the parts design without design changes due to an inadequate design procedure (e.g., a later-designed part does not affect earlier-designed parts). Moreover, using the structural model of functions, product planners and designers can comprehend the trade-off between elements and their effect, allowing them to properly determine the specifications or develop a new product.

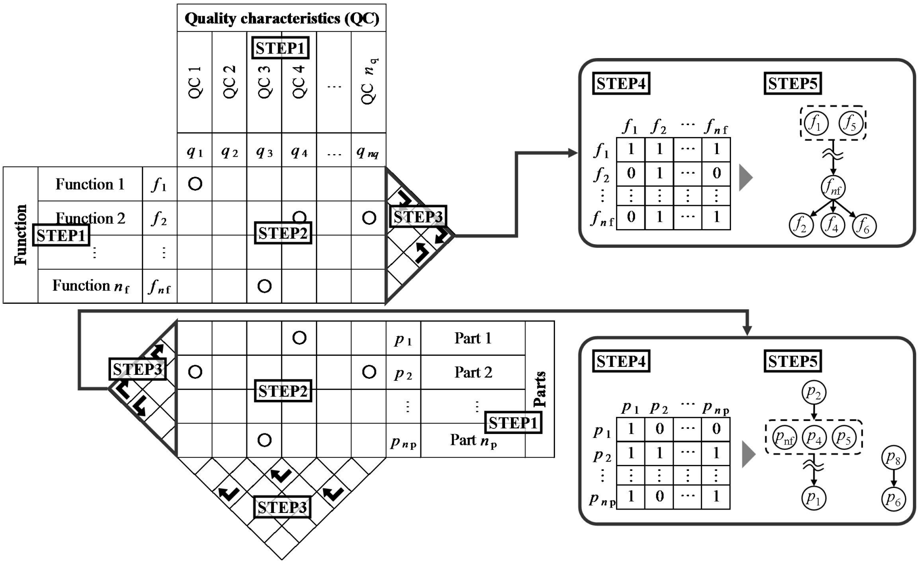
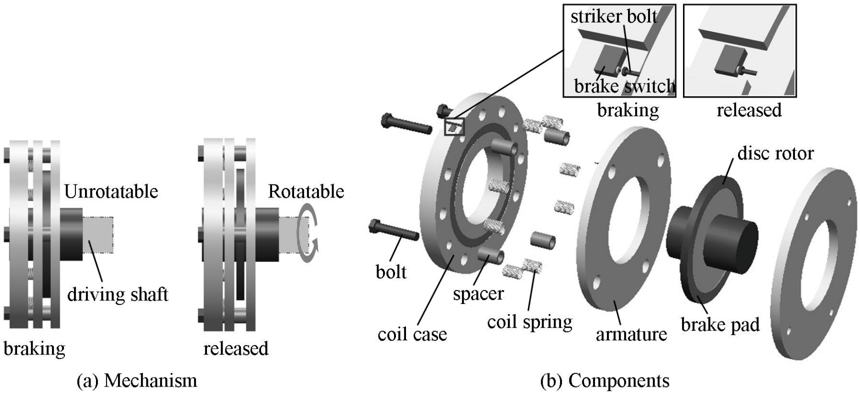


Fig. 5. Procedure of proposed QFD

4 Illustrative Example

4.1 Design Object

To confirm their effectiveness, the proposed quality matrices were applied to a design problem of a disc brake. This disc brake generates a brake torque by pushing the armature onto the disc rotor (brake pad) due to the spring force. Figure 6 shows a conceptual diagram of the disc brakes. The coil springs, which are located between the coil case and armature, push the armature onto the brake pad when braking.



(a) Mechanism (b) Components

Fig. 6. Conceptual diagram of disc brake

When releasing the brake, the armature is attracted to the coil case via an electromagnetic force. To sense that the brake is braking or releasing, the brake switch, which is installed on the coil case, is set and flipped by the striker bolt set on the armature.

In a disc brake design, designers or product planners must consider a lot of design elements (e.g., the spring characteristics related to the brake torque, the coil characteristics to specify the electromagnetic force, the armature stroke, which concerns both the drive noise and brake switch characteristics) to realize the ideal brake characteristics (e.g., high brake torque, low drive noise, no brake switch glitch). Because a trade-off relationship exists between these characteristics, a design change due to an inadequate design process is likely. Additionally, inadequate specifications may delay of the product development.

4.2 Results and Discussion

Figures 7 - 10 describe the proposed quality matrices and structural models of the disc brake, respectively. Figure 9a shows a structural model of the part elements without considering the quality characteristic relationships. This type of model provides information about the geometric relationships between parts, such as mechanical interference. For example, the part elements of the coil case (p_1–p_3) relate to the part elements of the spring mounted on the coil case. Figure 9b shows a structural model that considers relationships. This type of model indicates not only the geometric relationships but also the relationship regarding engineering characteristics, such as torque or electromagnetic force. For example, the part elements of the coil case (p_1–p_3) relate to the part elements of the spacer (which assures a brake gap) via electromagnetic force and armature stroke. To summarize, the structural model constructed by the proposed QFD expresses relationships of both the geometric and engineering characteristics (generated from the product). Thus, the proposed QFD allows engineering designers to easily construct modular parts or a design procedure using the parts.

The structural model of function elements that considers quality characteristic relationships (Fig. 10b) increases bidirectional relationships compared to the model that does not consider relationships (Fig. 10a). Consequently, the model that considers quality characteristic relationships clarifies the trade-off relationships due to the engineering characteristics, such as "smooth attraction and release" (f_1) and "power consumption" (f_6) or "sufficient brake torque" (f_2) and "lower noise" (f_4). This improved clarity allows product planners or designers to appropriately determine the specifications or develop new products.

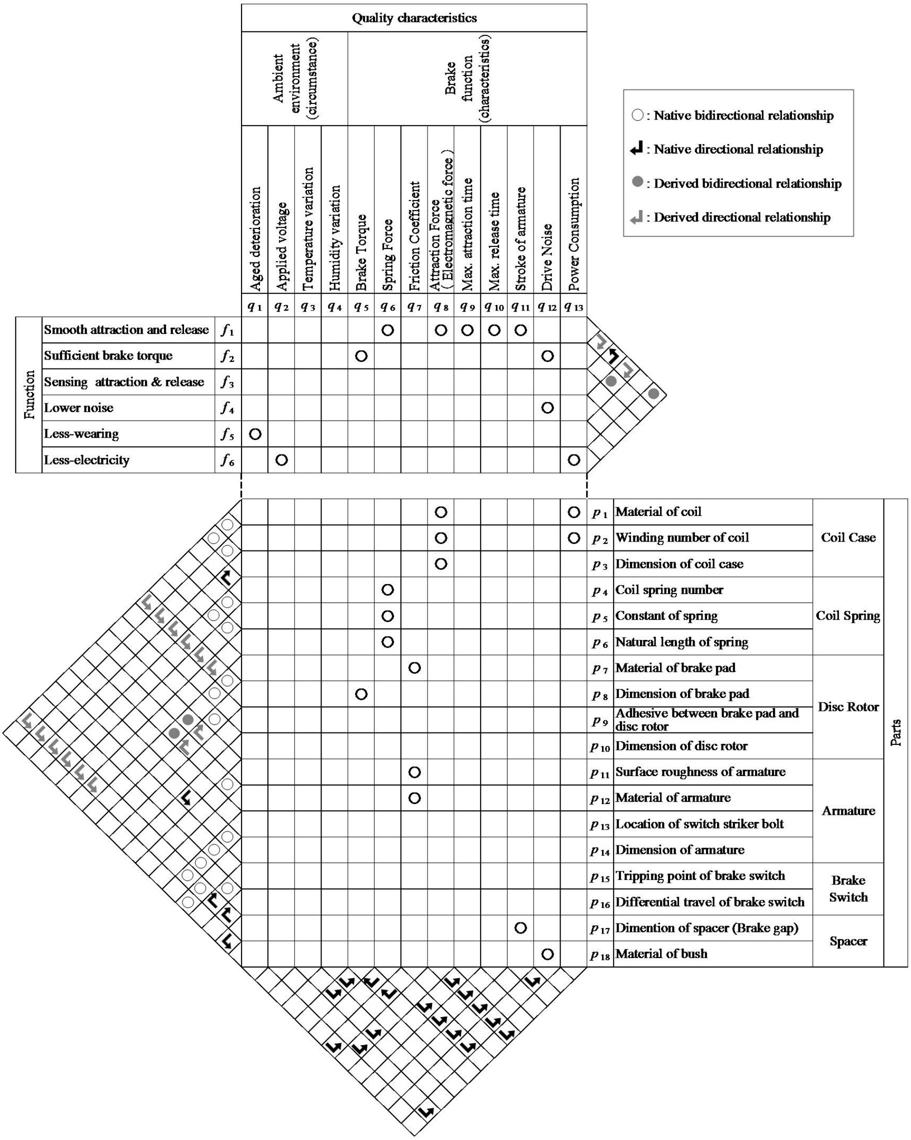


Fig. 7. Quality matrices of disc brake

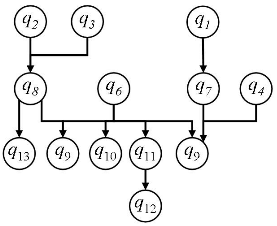
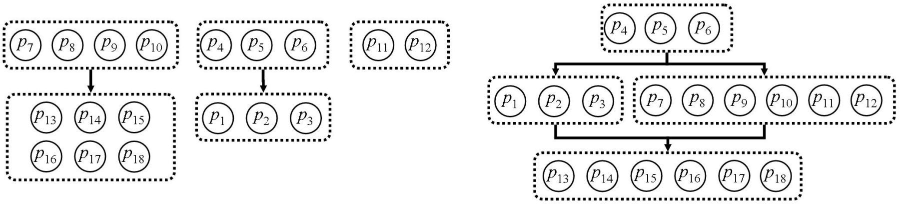
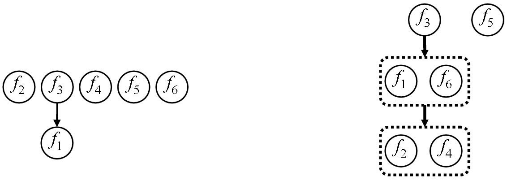


Fig. 8. Structural model of quality characteristic elements



(a) Without the quality characteristic relationships (b) Including the quality characteristic relationships

Fig. 9. Structural model of part elements



(a) Without the quality characteristic relationships (b) Including the quality characteristic relationships

Fig. 10. Structural model of function elements

5 Conclusion

To clarify the complicated relationships of the design elements, this study introduces improved Interpretive Structural Modeling (ISM) into Quality Function Deployment (QFD). The following observations are made:

- The structural models of the design elements (derived by the ISM) enable users to comprehend the relationships between design elements intuitively.
- The structural model of the part elements, which consider the quality characteristic relationships (derived by the improved ISM), allows engineering designers to comprehend both the geometric relationships of the parts and the relationships based on the engineering characteristics. This improved understanding aids engineers in constructing the modular parts or design procedures for the parts.
- The structural model of the function elements, which consider relationships, enables product planners or designers to understand the trade-off relationships

between the function elements generated by the engineering characteristics. This assists planners or designers in determining the proper specifications or developing new products.

Additionally, the applicability of the proposed QFD was confirmed by applying it to a design problem of a disc brake. In the future, the proposed QFD will be implemented to many other design applications.

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