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Quality Function Deployment Applying Structural Model

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***Abstract*—Sharing the product information between the product development members has been important due to the product diversification and complication. Quality Function Deployment (QFD) is an effective method to share the information of the product via 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) that visually expresses the complex relationship between them. The proposed QFD was applied to a head protection wear design problem.**

***Keywords*—design theory and methodology, Quality function deployment, Interpretive structural modeling**

I. Introduction

Product functions and mechanisms have diversified and 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 reconsideration or quality issues in the design process. To share the information between design members, many methods have been proposed. Product designers or planners often use the KJ method to determine the concept or specifications of a product in the early process of design, while mechanical designers or manufacturing designers employ Fault Tree Analysis (FTA) or Failure Mode and Effects Analysis (FMEA) to confirm the reliability and safety of a product in the later process of design. However, neither of these methods is applicable throughout the entire design process (i.e., early and later processes).

Quality Function Deployment (QFD) 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 engineering 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.

A primitive QFD was proposed by Akao in 1966, and it clarified important design elements in the product manufacturing process using the production process assurance items charts [2,3]. These assurance charts are composed of both a cause-and-effect diagram to clarify the important production process elements with respect to quality assurance items within a company and relationship matrices to transform the quality assurance items within the company into those outside the company [3]. The conventional version of QFD was improved in 1976. Since then, companies around the world have employed QFD. An improved QFD (hereafter called basic QFD), can be used in the early process of design by adding a demanded quality (customer demands) and the quality characteristics (engineering characteristics) deployment charts. The basic QFD contains several quality charts:

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

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 basic 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 [4-6,7], (ii) change in the items of the quality charts [8-11], (iii) usage assistance [12-15].

Although there are many proposals regarding QFD, these may be insufficient because product design is constantly changing. (Product design is diversifying and becoming more complicated.) Our research aims to analyze the necessity of QFD in product design and to improve QFD based on the results. This research focuses on product design process (e.g., conceptualization, specification, appearance, and mechanical design) and excludes other processes (e.g. manufacturing design, installment, and maintenance).

This paper is organized as follows. Section 2 analyzes the requirements for QFD and discusses the method to meet them. Section 3 overviews the selected method and the improved QFD based on it. Section 4 illustrates an application of the proposed QFD to a head protection wear, while Section 5 provides conclusions and the future research direction.

II. Analysis of the requirements for and clarification of the measures to improve basic QFD

A. *Analysis of the requirements*

To extract the requirements for QFD, we focus on basic QFD (Fig. 1) because latter QFDs are specialized for a specific design or objective, making it difficult to extract the general requirements from these latter QFDs. Table 1 lists the

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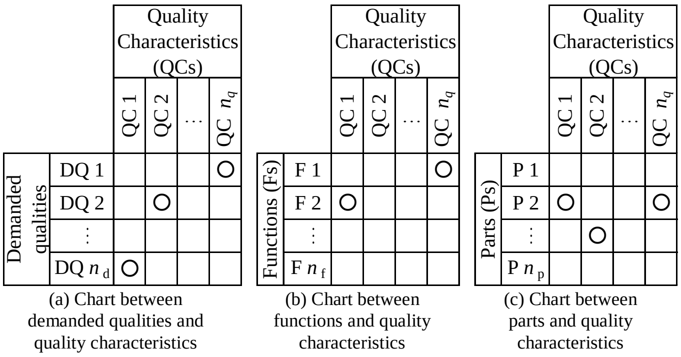


Figure 1. Conceptual diagram of quality matrices

Table 1. Requirements for QFD

	Requirements for QFD	References
1	Constructing proper design process of parts	[16,20]
2	Balancing quality and cost	[3,16,17]
3	Extracting elements of entirely new products	[16,18,20]
4	Sharing information between product design members	[3,17]
5	Understanding relationships between elements in deployment chart	[3,17]
6	Extracting product users or surrounding environment	[18,20]
7	Extracting elements of product using new technology	[18,20]
8	Extracting company requirements	[19]
9	Handing down engineering skills to successors	[20]
10	Extracting society requirements	[20]
11	Setting of standard parts and modular parts	[20]
12	Extracting environment requirements	[20]

extracted requirements from the literature with regard to the application of basic QFD [3,16-20] that remain after removing the requirements generated from the differences in experience or individual competence of the designers (e.g. "elimination of the bottleneck regarding design elements in QFD" and "properly weighting of the design elements").

Herein we conduct a pair comparison between the requirements, and analyze the results using multidimensional scaling and cluster analysis. The degree of similarity between the requirements ranges from 1 (very similar) to 5 (not similar), and the average value of the degrees evaluated by ten products and engineering designers from various manufacturing companies (Fig. 2a). Fig. 2b and 2c show the scatter graph by the multidimensional scaling (including two ellipses that express the design element groups derived by the cluster analysis method) and the dendrogram by the cluster analysis method, respectively. This study employs the PROXSCAL algorithm for multidimensional scaling and Ward's method as a cluster analysis method.

As shown in Fig. 2, the requirements are classified in two groups. One extracts diverse design elements, including "company requirements" and "product users or surrounding environment". The other comprehends the information from the extracted design elements and their relationships that contains "relationships between elements in deployment charts" and "proper design process of the parts". This research focuses on the latter group and reanalyzed the requirements of the group in the same way. They are, consequently, classified in two groups:

1) One organizes the design elements that contain "balancing quality and cost" and "setting of standard parts and modular parts";
2) The other sequences the design elements, including "constructing design process of parts", "understanding relationship between elements in deployment chart", etc.

On the basis of the two groups, this study discussed the methods to improve QFD employing the two features: "grouping the elements" and "stratifying the elements" as detailed in the next section.

B. *Clarification of the measures to improve the QFD*

The promising methods for improve the QFD were extracted from the previous study [21] that constructs a classification scheme for analysis methods in design field. These methods enable designers to comprehend the relationship between all design elements (not between the focused elements) and are given as follows: 1) Affinity diagram, 2) Protocol analysis, 3) Petrinet, 4) DEMATEL, 5) Interpretive structural modeling (ISM), 6) Correspondence Analysis, 7) Self-organizing map, 8) Quantification Theory type Ⅲ, 9) Quantification Theory type Ⅳ, 10) Dual scaling method, 11) Rough sets, 12) Factor analysis, 13) Cluster analysis, 14) Identify mapping model, 15) Principal component analysis, 16) Multi-dimensional scalling. They were compared with respect to the two features shown in section 2A. The comparison extracts affinity diagram [22] and ISM [23] that meet the two features. However, affinity diagram can express inclusive relationships but not causal relationships. This means it is unsuitable for expressing the relationships between the design elements in QFD because they are already assigned to the primary or secondary level (primary level elements include the secondary level ones) in the quality matrices and must have causal relationships. Additionally, it has the following shortages because it relies on the designers' intuition: 1) The repeatability between the users is low; 2) The users cannot consider the subsidiary effects of the elements when the element number is large. Therefore, this study decided to apply ISM to QFD. The outline of ISM is shown in the next section.

III. QFD based on interpretive structural modeling

A. *Interpretive structural modeling*

ISM is a design method to visually express complex relationships between design elements via matrix operations [23]. In ISM, direct affective matrix **X** (Fig. 3a), which expresses the relationship between n design elements, is initially constructed according to the following equation:

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

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

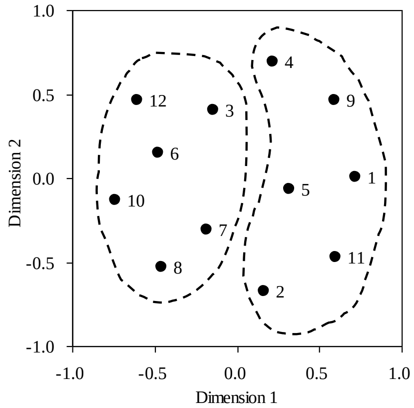
$$x_{ij} = \begin{cases} 1 & \text{if } i \text{ th element relates to } j \text{ the element} \\ 0 & \text{else} \end{cases} \quad . \quad (2)$$

$$(i = 1, 2, \cdots, n \ \ , \ \ j = 1, 2, \cdots, n)$$

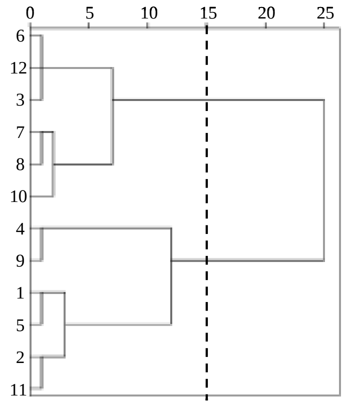
Secondly, reachable matrix $\mathbf{M}_R$ (Fig. 3b) is derived using

		Requirements											
		1	2	3	4	5	6	7	8	9	10	11	12
Requirements	1	0.0	2.2	3.9	2.9	2.7	2.3	1.8	2.1	1.9	3.3	3.5	3.8
	2		0.0	3.5	2.4	2.7	2.6	3.3	2.8	2.7	3.3	1.6	1.9
	3			0.0	2.2	2.9	2.5	2.9	3.4	3.5	1.9	2.7	2.7
	4				0.0	2.3	2.4	2.7	2.9	2.9	2.7	2.0	2.4
	5					0.0	1.5	2.4	1.8	2.0	4.1	3.7	3.0
	6						0.0	2.3	2.3	2.4	3.2	3.1	3.3
	7							0.0	2.6	2.9	3.4	3.1	3.0
	8								0.0	1.9	4.2	4.4	3.5
	9									0.0	3.6	4.2	3.6
	10										0.0	2.5	1.9
	11											0.0	2.3
	12												0.0

(a) Pairwise comparison matrix



(b) Scatter graph by multidimensional scaling



(c) Dendrogram by cluster analysis method

Figure 2. Result of multidimensional scaling and cluster analysis method

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

(a) Direct affective matrix

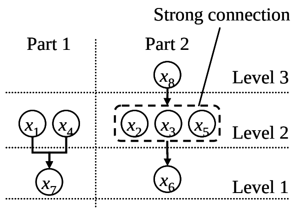
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
x_1	1	0	0	0	0	0	1	0
x_2	0	1	1	0	1	1	0	0
x_3	0	1	1	0	1	1	0	0
x_4	0	0	0	1	0	0	1	0
x_5	0	1	1	0	1	1	0	0
x_6	0	0	0	0	0	1	0	0
x_7	0	0	0	0	0	0	1	0
x_8	0	1	1	0	1	1	0	1

(b) Reachable matrix

Part 1 / Part 2; Level 1 / Level 2

		l_1	l_2		l_1	l_2	l_3
		x_7	x_1	x_4	x_6	x_2'	x_8
l_1	x_7	0	0	0	0	0	0
l_2	x_1	1	0	0	0	0	0
	x_4	1	0	0	0	0	0
l_1	x_6	0	0	0	0	0	0
l_2	x_2'	0	0	0	1	0	0
l_3	x_8	0	0	0	0	1	0

(c) Skeleton matrix



(d) Structural model

Figure 3. Conceptual drawing of ISM

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:

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

where the calculation is based on Boolean operations. Finally, reachable matrix $\mathbf{M}_{\mathrm{R}}$ is transformed into skeleton matrix $\mathbf{M}_{\mathrm{S}}$. This paper omits the detailed calculation of the skeleton matrix because it has already been reported [23]. Skeleton matrix has two main features: 1) elements are classified into parts in which an element has at least one relationship with other element. 2) elements are classified into levels where the elements in the higher level affect more elements. Thus, ISM can simultaneously group and stratify. Skeleton matrix (Fig. 3c) is used to construct the structural model (Fig. 3d) that makes the designers to easily comprehend the relationships of the elements.

B. *QFD with interpretive structural modeling*

To apply ISM, this study introduces a correlation matrix into each of the three deployment charts in QFD. Fig. 4

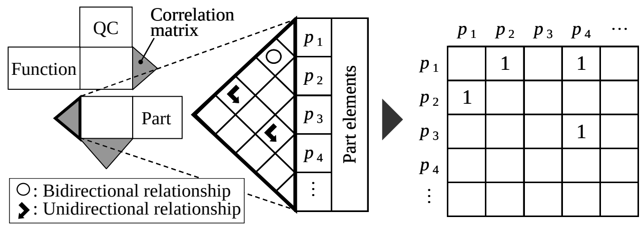


Figure 4. Correlation matrix and its direct affective matrix

shows a conceptual drawing of the correlation matrix and the direct affective matrix derived from it. In the correlation 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 ○. The structural model derived via ISM enables designers to comprehend the relationships of the elements in each category (function, QC, or part). However, the relationships in each category are insufficient in the actual design. For example, in a seat design, "longitudinal elastic modulus of seat cushion" and "seat cushion angle" (part elements) are not directly related. However, they are actually related because both of them relate a same QC element of "shear force at user buttocks" (i.e. the two part elements should be designed considering the QC element).

This study added the QC element relatinships to the function and part element ones because the QC elements that express the product characteristics are constrained (focused) and affect the function and part elements in most cases. For example, in the automobile or architectural design, the QC elements such as "impactive force absorptance" or "fatigue strength" are constrained (to comply with safety standards) and affect the part and function elements such as "shape", "material", "highly manufacturable", or "material saving". However, some design objects focus on the relationship other than QC elements, such as service design that mainly focuses on the human activities (function elements) and product design that intensely focuses on the appearances (part elements). In the case, the focused element relationships should be added to others.

The procedure below clarifies the part element relationships while considering the QC element relationships using ISM. Because the procedure for the function relationships is the same as that for the parts relationships, its description is abbreviated. To consider the

QC element relationships, the following two rules are added to construct a correlation matrix referring to a previous study [24]. 1) Bidirectional relationships must be derived between part elements related to a common QC element (Fig. 5a). 2) Unidirectional relationships of the part elements in the same direction must be derived as the relationship of the QC elements that relate to the part elements (Fig. 5b).

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

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

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 QC elements $\mathbf{Q}$ in the i th row and j th column. (p_m, q_n) represents the value of the relation matrix between the QC and part elements in the m th row and n th column. n_p and n_q denote the number of the part and QC elements, respectively. Similarly, the direct affective matrix with regard to the second rule $\mathbf{P}^{2)}$ is expressed as:

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

By adding (4) and (5) to the original direct affective matrix of part elements $\mathbf{P}$, the direct affective matrix that considers QC element relationships $\mathbf{P}'$ can be calculated as:

$$\mathbf{P}' = \mathbf{P} + \mathbf{P}^{1)} + \mathbf{P}^{2)} \quad . \quad (6)$$

The structural model of part elements via ISM using the direct affective matrices expresses the organized designer's ideas and enables the designers to proceed with the parts design without the design reconsideration due to an inadequate design procedure (e.g. a later-designed part does not affect earlier-designed parts). Moreover, using the structural model, other designers can comprehend the designer's idea and efficiently work on the redesign or design change of the product.

IV. Illustrative example

A. Design object

To confirm the applicability of the proposed QFD, it was applied to a design problem: the redesign of a head protection wear (HPW). HPWs are used by the people who are likely to faint and required to absorb shock to the head. Therefore, conventional HPWs are composed of expanded polyethylene (EPE) to absorb shock and artificial leather to cover the EPE and to shape the HPWs (Fig. 6a). However, artificial leather has poor ventilation, which makes it uncomfortable to wear for several hours.

Instead of artificial leather, the redesign employs three-dimensional knitting. Pile yarn links the surface and

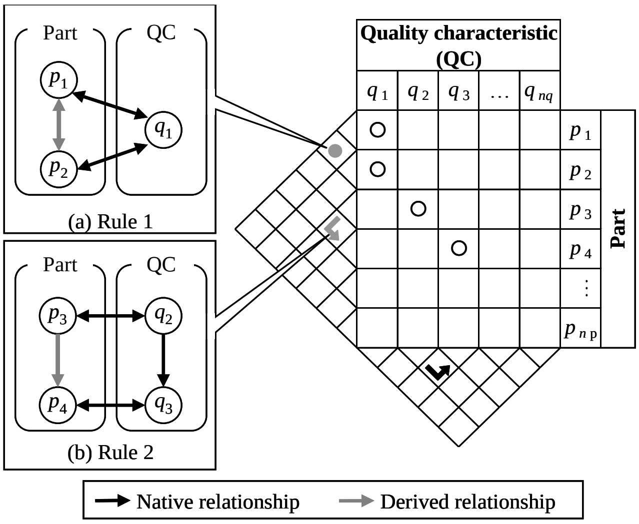


Figure 5. Derived relationships between part elements based on the state elements relationships

Figure 6. Head protection wear [2]

backing fabrics (knitting fabrics), which are also employed in soft-cases of laptops. This design provides ventilation, shock absorption, and shape stability.

B. Results and discussion

The redesigned HPW is shown in Fig. 6b. The quality matrices including the correlation matrices and the structural model of the function and part elements based on them are shown in Fig. 7, 8, and 9, respectively. Fig. 8 and 9 contain both of structural model with and without considering QC elements for comparison. Fig. 8a shows a structural model of the part elements without considering the QC element relationships. This type of model provides information about the direct relationships between part elements, such as assembling parts. For example, the part element combination of "front and back surface of 3D knittings" (part elements a_1 and a_2) or "side belt" and "hock and loop fastener" (a_7 and a_9). Whereas, Fig. 8b shows a structural model that considers the QC element relationships. This type of model indicates not only the direct relationships but also the subsidiary relationship regarding engineering characteristics, such as "longitudinal elastic

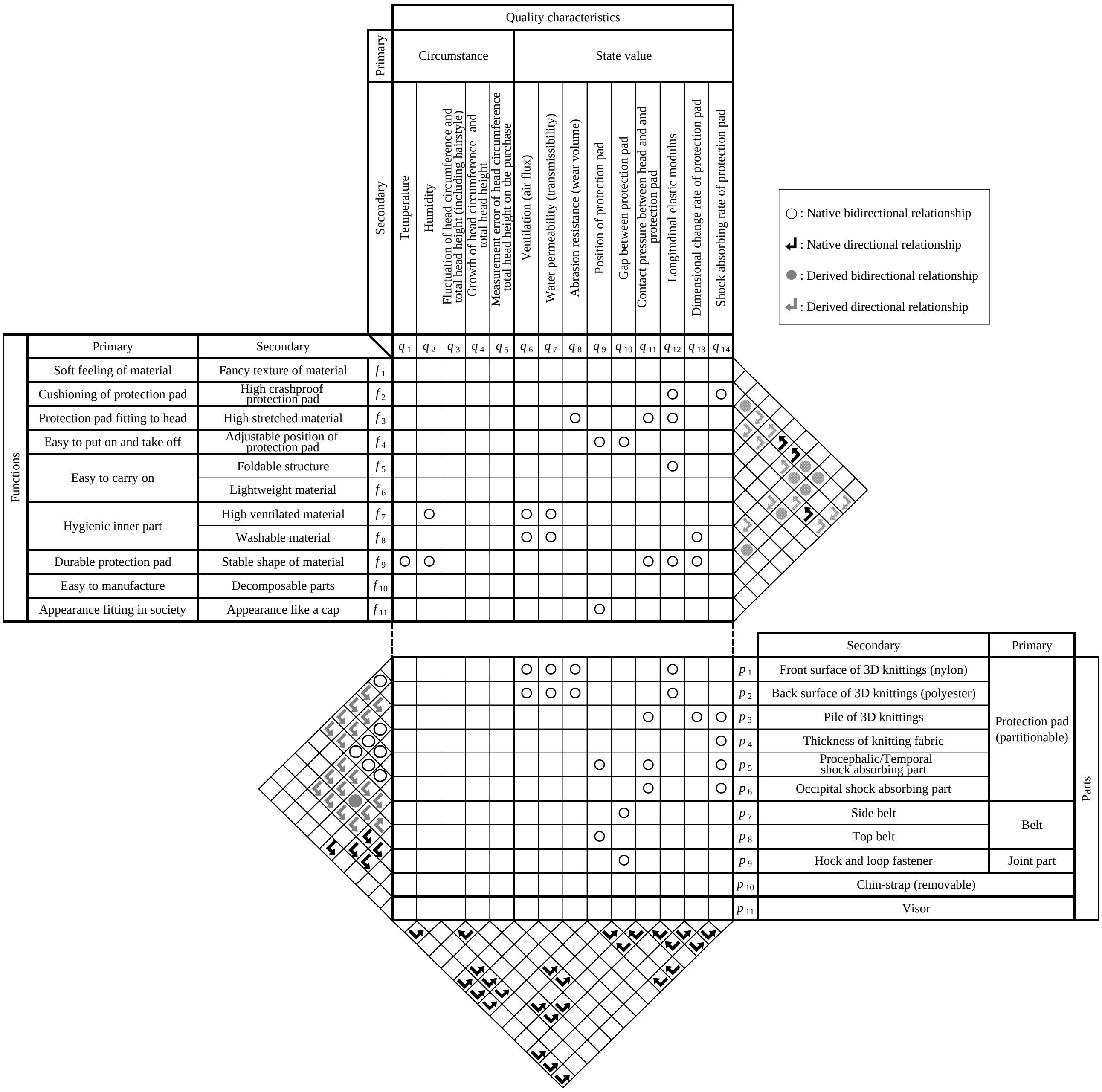
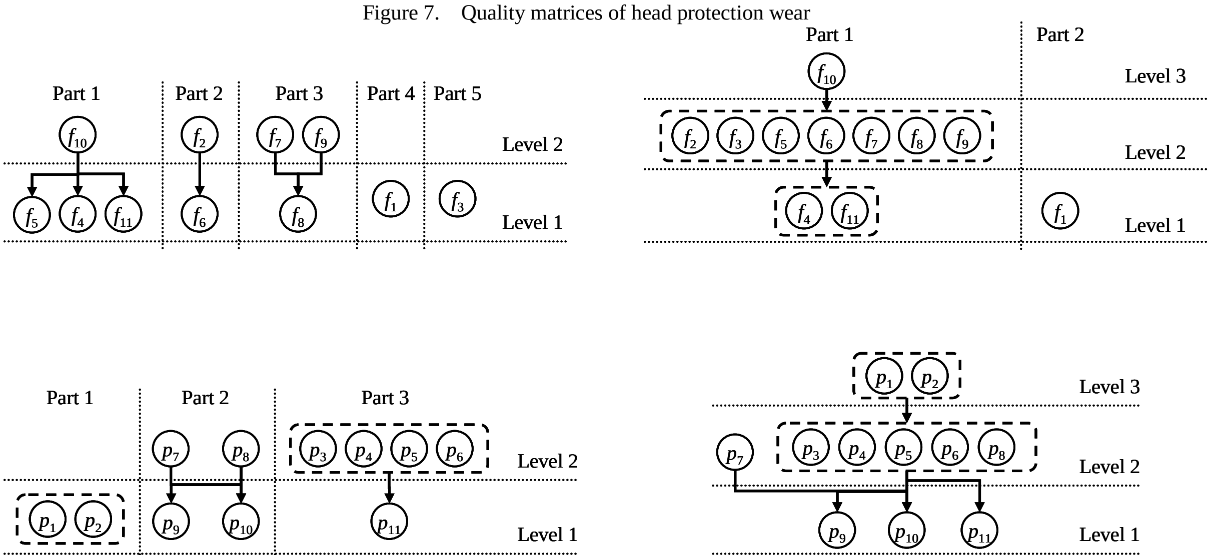


Figure 7. Quality matrices of head protection wear



(a) Without the QC element relationships

(b) Including the QC element relationships

Figure 9. Structural models of the function elements

modulus" and "shock absorbing rate of protection pad" (QC elements s_{12} and s_{14}). For example, "front and back surface of 3D knittings" (a_1 and a_2) relate to "thickness of knitting fabric" (a_4) via "longitudinal elastic modulus" and "shock absorbing rate of protection pad". To summarize, the structural model of the part elements constructed via ISM expresses relationships of both the direct and indirect, such as the relationships regarding assembling or via engineering characteristics. Thus, the proposed QFD with ISM gives the design information to other designers and allows them to easily construct a design process without an inadequate order of design causing the design reconsideration.

The structural model of function elements that considers QC element relationships (Fig. 9b) increases bidirectional relationships compared to the model that does not consider the relationships (Fig. 9a). This means the model that considers QC element relationships clarifies the product functions (function elements) that should be considered simultaneously due to the engineering characteristics. For example, "adjustable position of protection pad" (m_4) and "appearance like a cap" (m_{11}) relate each other via "position of protection pad" (s_9). This means another mechanism for adjusting the protection pad to a proper location should be considered when the conventional appearance (Fig. 6a) is changed to one like a cap (Fig. 6b). This is an idea of the designer who made the quality matrices and suggests other designers to consider the two function elements simultaneously. To summarize, the structural model of the function elements expresses product functions that should be considered simultaneously in the design process. Therefore, the proposed QFD with ISM has possibilities to allow designers to appropriately determine the specifications or develop new products.

V. Conclusion

To comprehend the information from design elements and their relationships, this study introduced Interpretive Structural Modeling (ISM) into Quality Function Deployment based on Multi spaces (QFD). ISM stratifies and groups the design elements that belong to each of the three correlation matrices in QFD: function, QC, and part and constructs structural models of them that visually express their relationships. This study additionally proposed a method to add the relationships of the correlation matrix including design constraints to another one. The proposed QFD with ISM gives information of the design (designer's idea) to other designers and enables them to easily construct a design process without an inadequate designing order causing the design reconsideration. This means it has effects not only in the development of a new product but also in the redesign or design change of the product.

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

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