CLUSTERING METHOD OF DESIGN STRUCTURE MATRIX FOR TRADE-OFF RELATIONSHIPS

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Abstract: Due to the specialization and professionalization of design activities, sharing the product information between the members of a product development team has become important. In the previous study, we proposed M-QFD by applying the concept of Multi-space design model to QFD (quality function deployment) and the modularization method, which arranges the relationships between the diverse design elements extracted using M-QFD and modularizes (clusters) the product components. However, the clustering method has difficulty in deriving the adequate number of the clusters because the more types of the interactions become, the more the number of the trade-off relationships between the components included in a cluster. This paper presents the clustering method dealing the trade-off relationships between the product components. This method can support designers to integrate or decompose the components on the basis of the trade-off relationships. Moreover, this paper describes the illustrative example of the proposed method.

Keywords: Design Structure Matrix (DSM), DSM Clustering, Trade-off Relationships, Quality Function Deployment (QFD)

1. Introduction

The requirements and functions/mechanisms of products have diversified and become complicated respectively, resulting in the specialization and professionalization of the product development work. Consequently, it is difficult for the members of a product design team (i.e., planner, industrial designer, and engineering designer) to share the product information [1].

In the previous study, we proposed M-QFD by applying the concept of Multi-space design model to QFD (quality function deployment) [2, 3]. This method can extract the design elements related to the requirements of the diverse stakeholders for the products and arrange the relationships of them. The design elements mean something related to the design object and are classified into the following four types based on the Multi-space design model: 1) the value elements that represent the values for the users, company, and society and are given by the design object, 2) the meaning elements which mean the functions and the images of the design object, 3) the state elements including the physical properties of the design objects and the ambient environment surrounding them, 4) the attribute elements that denote the components and the materials of the design object.

Moreover, we improved M-QFD to reflect the relationships of the psychological design elements dealt by the designer into the relationships of the physical design elements dealt by the engineering designer and proposed the method to modularize (cluster) the product components [4]. The proposed modularization method firstly transfers the relationships between the value, meaning, and state elements in M-QFD into the relationships of the attribute elements (i.e., product components). Then, the method constructs the DSM (Design Structure Matrix) of the attribute elements and clusters them on the basis of the relationships using Ogawa’s clustering method [5]. DSM, which is a design management tool, sets the design elements (e.g., the components, the tasks, and the teams) in both the row and column in the matrix and groups their relationships (i.e., conducts a clustering) or sequences the flow of the influences (i.e., conducts a partitioning) in order to organize the relationships between them. Ogawa’s clustering
method, on the other hand, derives the clusters based on each type of the relationships between the components (hereinafter called interactions), such as the adjacency and the input-output of the energy exchange. Then, the cluster based on one type of interactions are integrated the cluster based on another type having the components of its cluster. This method, therefore, can cluster the components considering some types of the interactions between them.

However, this method, which integrates some clusters with many unrelated the components, has difficulty in deriving the adequate number of the clusters because the more types of the interactions become, the more the number of the components included in a cluster tends to be large. The clustering methods similar to the aforementioned method dealing some types of the interactions have been studied in the area of the component-based DSM.

Therefore, this study reviewed the conventional clustering methods for the component-based DSM and developed the clustering method to solve the above problem. This paper is organized as follows. Section 2 introduces the conventional clustering methods and discusses about the possibility that they solve the aforementioned problem. Section 3 describes the proposed clustering method. Section 4 illustrates an application of the proposed method to an automotive steering system, while Section 5 provides conclusions and the future research direction.

2. Review of conventional clustering methods for component-based DSM and their applicability against clustering problem

2.1. Conventional clustering methods

The component-based DSM includes some types of the interactions between the product components in order to cluster them. The procedure of the component-based DSM is described in Figure 1 [6].

First, quantify the interactions and fill the values (hereinafter called evaluation values) in the matrix (Figure 1 (a)). Some quantifying rules (i.e., definitions of the quantified values) are described as examples: 1) “+1” (if the interaction exists) or “0” (if the interaction does not exist); 2) “+2” (if the stronger interaction exists), “+1”, or “0”; 3) “+2”, “+1”, “0”, “-1” (if the detrimental interaction exists), or “-2” (if the stronger detrimental interaction exists). Second, derive the integrated evaluation value calculated from the evaluation values regarding all types of the interactions (Figure 1 (b)). Finally, identify the groups (clusters) of the components having the strong interactions each other by arranging the large integrated evaluation values close to the diagonal components of the matrix (Figure 1 (c)).

The conventional clustering methods for the component-based DSM are differentiated not only by the types of the evaluation values but also by the calculating methods of the integrated evaluation values. Table 1 summarizes the concept and the differences of the clustering methods. The details are described as follows.

Eppinger proposed the clustering method which defines the evaluation values of the interactions between the components using the following five-point scale [7]: “+2” (if the interaction is necessary for the components), “+1” (if the interaction is beneficial, but not absolutely necessary for the components), “0” (If the interaction is indifferent), “-1” (if the interaction causes the negative effect, but does not prevent for the components), “-2” (if the interaction must be prevented for the components). For example, in an automotive air-conditioning control system design, a compressor receives the refrigerant gas and transfers the high press gas to a condenser. The interaction between the two components is an exchange of the heat energy and necessary for the system. Thus, it is evaluated as “+2”.

This method defines the integrated evaluation value as an evaluation value of the most important interaction type selected by the designer. This method, therefore, can employ the positive and negative evaluation values of the most important interaction type and can cluster the components on the basis of them.

Bready developed the clustering method which defines the evaluation values using the following three-point scale [8, 9]: “+2” (if the interaction of the energy, the physical adjacency, or the direct information exchange exists), “+1” (if the indirect information adjacency exists), “0” (if the interaction does not exist). This method calculates the integrated evaluation value as the sum of the evaluation values of each interaction. This method, therefore, can cluster the components on the basis of the strength of the interactions using only the positive evaluation values. The reason of employing the positive values is to avoid the positive and negative evaluation values cancel out each other.

Similar to Bready’s method, Sharman provided a clustering method [10-12]. This method employs the sum of the evaluation values of each interaction same as Bready’s method but does not employ the evaluation values “+2”. This method, therefore, can cluster the components on the basis of the number of the interaction types between them.

Deng proposed the clustering method which defines the evaluation values using 1/0 [13]. This method calculates the integrated evaluation value as the linear sum of the evaluation values and the weights of the interaction set by the designer whose sum is 1. This method, therefore, can cluster the components on the basis of the positive evaluation value and the
weights based on the importance of each interaction.

Helmer’s method defines the evaluation values using the following seven-point scale [14, 15]: “+2” (if the interaction is necessary and required the spatial adjacency for the components), “+1” (if the interaction is necessary, but not absolutely required the spatial adjacency for the components), “+0.5” (if the interaction is beneficial, and exist the weak spatial adjacency for the components), “0” (if the interaction is indifferent), “-0.5” (if the interaction cause the negative influence if the spatial adjacency for the components), “-1” (if the interaction must be prevented, but not absolutely separated the spatial adjacency for the components), “-2” (if the interaction must be prevented and separated the spatial adjacency for the components). This method integrates the evaluation values using the rule of the integrated evaluation values, which represents the importance of them (Figure 2). As shown in Figure 2 (a), the upper the evaluation value locates, the higher the importance becomes. The evaluation values of all the interaction types are compared on the basis of the rule, and the highest important evaluation value is chosen (set) as the integrated evaluation value. Note that a pair of “+1” and “-1” or that of “+0.5” and “-0.5” between the components are considered as the weak interactions, and its integrated evaluation value set to “0”. This method, therefore, can choose the integrated evaluation value from the positive and negative evaluation values using the rule and can cluster the components on the basis of them.

2.2. Applicability of conventional clustering method against clustering problem

To solve the problem mentioned in Section 1: “it is difficult to assure the adequate number of the clusters due to become larger the components including each cluster”, it is required not only to generate the clusters using the positive evaluation values but also to decompose the clusters using the negative ones. Moreover, if both the positive and negative evaluation values exist between a pair of the components, the clustering method is
required to support designers to integrate or decompose the components on the basis of the values. In other words, the clustering method requires the proper way to evaluate the trade-off relationships between the components.

The aforementioned conventional methods can be classified into two types: the methods using the positive evaluation values and those using both the positive and negative evaluation values. The former methods include Bready’s, Sharman’s, and Deng’s methods and define the integrated evaluation value as the sum or linear sum of the evaluation values. On the other hand, the latter methods include Eppinger’s and Helmer’s methods and define the integrated evaluation value as an evaluation value chosen by the designer or the rule of the integrated evaluation values.

The insufficiency of both the types of the methods against the clustering problem are described as follows. The former methods operate only the positive evaluation values in order to prevent the positive and negative evaluation values cancel out each other when the sum of them (the integrated evaluation value) is calculated. On the other hand, the latter methods extract one of the evaluation values as an integrated evaluation value. This means they cannot consider the evaluation values of all the interaction types. Therefore, the conventional methods cannot consider all the evaluation values of all the interaction types including negative evaluation values. In other words, these methods cannot evaluate the trade-off relationships between the components. The trade-off relationship means both the positive and negative evaluation values exist between a pair of components (i.e., “+2” and “-2”; “+1” and “-1”).

Therefore, we proposed a clustering method for evaluating the trade-off relationships. The next section illustrates the detail of the proposed method.

3. Clustering method for evaluating trade-off relationships

3.1. Method for evaluating trade-off relationships

The conceptual drawing of the proposed clustering method is described in Figure 3. In this figure, “P”, “N”, and “T” denote the pairs of the components having only the positive evaluation values, only the negative ones, and the positive and negative (trade-off) evaluation values, respectively. The proposed clustering method employs two types of the clustering to evaluate the trade-off relationships between the components: First one collects the components using the positive evaluation values and generates the clusters including the trade-off relationships (e.g., the cluster {A, C, D, E} in Figure 3 (b)). The other one decomposes the generated clusters into the sub-clusters using the negative evaluation values (e.g., the clusters {A, D} and {C, E} in Figure 3 (c)). This clustering locates the trade-off relationships out of the sub-clusters in each cluster. This enables designers to comprehend the trade-off relationships between the components and to decide a suitable cluster composition. The detail of the method for evaluating the trade-off relationships in the two types of the clustering are described as follows.

The prior clustering is required to collect the components including not only the positive evaluation values but also the trade-off relationships. This study, therefore, proposed a rule of the integrated evaluation values to prioritize the components including the positive evaluation values or the positive and negative evaluation values (Figure 4 (a)). In other words, the rule chooses the evaluation value whose absolute value is the largest in the values of each pair of the components and sets it as the integrated evaluation value. Note that this rule prioritizes the positive evaluation values when the absolute values are equivalence. For example, in Figure 4 (b), the integrated evaluation values are “+2” and “-2” when there are the evaluation values: {“+2”, “-2”} and {“-2”, “+1”}, respectively. Thus, the integrated evaluation values of the trade-off relationships whose evaluation values have the same absolute value and a different sign (“+” / “-”), are positive, and the components having the trade-off relationships are clustered with those having the positive evaluation values (Figure 3 (b)).

The latter clustering is required to extract the trade-off relationships in the clusters identified by the prior clustering and to derive the sub-clusters. This study, therefore, constructed the other rule to prioritize the components including the negative evaluation values (Figure 5 (a)). The rule sets the evaluation value whose absolute value is the largest as the integrated evaluation value same as the rule of the prior clustering but prioritizes the negative evaluation values when the absolute values are equivalence. For example, in Figure 5 (b), the integrated evaluation values are “-2” and “+2” when there are the evaluation values: {“-2”, “-2”} and {“+2”, “-1”}, respectively. Thus, when the evaluation values have same absolute value and a different sign, the negative one is selected as an integrated evaluation value. This can distinguish the components having the trade-off relationships from those having only the positive evaluation values (Figure 3 (c)).

3.2. Clustering algorithm

Addition to the method for evaluating the trade-off relationships between the components aforementioned in Section 3.1, the proposed clustering method needs the method to identify the clusters (hereinafter called clustering algorithm) to improve the evaluation. This study adopted the clustering algorithm [16, 17] employed by Helmer because similar to Helmer’s method, the proposed method clusters using the
positive evaluation values and generates the clusters including the trade-off relationships (e.g., the cluster \{A, C, D, E\} in components: First one collects the components using the negative (trade-off) evaluation values, respectively. The value \(V\) is calculated. On the other hand, the latter methods prevent the positive and negative evaluation values cancel out methods and define the integrated evaluation value as the sum of both the positive and negative evaluation values when the absolute values are same.

The former methods include Bready and those using both the positive and negative evaluation values. Therefore, we proposed a clustering method for evaluating the trade-off relationships between the components. In other words, the required to support designers to integrate or decompose the components on the basis of the values. In other words, the cluster composition. The detail of the method for evaluating the trade-off relationships in the two types of the clustering are described as follows. First step set \(S\) the genes of the genetic algorithm (Figure 6 (a)). The number of the genes in each individual is \(n_v\) and the components number. The matrix has the interactions only between all the components belonging to in the same cluster (Figure 6 (b)). Third step searches the optimal individual on the basis of the fitness \(F\) calculated as the following equation.

\[
F = (1 - \alpha - \beta)(n_c \log n_c + \log n_{c1} \sum_{i=1}^{n_c} c_{i1}) + \alpha(\sum_{i=1}^{n_v} n_{vi} \log n_{vi} + 1) + \beta(\sum_{i=1}^{n_c} n_{ci} \log n_{ci} + 1)
\]

where, \(n_c\) and \(n_v\) are the numbers of the clusters and components respectively; \(c_{i1}\) is the number of the components in the \(i\)-th cluster. \(S_1\) and \(S_2\) are the values of the mismatches between the given matrix and the OCD and calculated as the following equations.

\[
S_1 = \sum_{i=1}^{n_v} \sum_{j=1}^{n_v} O_{ij} \left\{ \begin{array}{ll}
1 - \frac{d_y - d_{\min}}{d_{\max} - d_{\min}} & \text{if } d'_{ij} = 1 \\
0 & \text{if } d'_{ij} = 0
\end{array} \right.
\]

\[
S_2 = \sum_{i=1}^{n_v} \sum_{j=1}^{n_v} O_{ij} \left\{ \begin{array}{ll}
0 & \text{if } d'_{ij} = 1 \\
\frac{d_y - d_{\min}}{d_{\max} - d_{\min}} & \text{if } d'_{ij} = 0
\end{array} \right.
\]

where, \(O_{ij}\) is the value of the mismatch between an identical pair of the components in the given matrix and the OCD. \(d_y\) and \(d'_{ij}\) represent the evaluation values of the given matrix and the OCD, respectively. \(d_{\max}\) denotes the maximum evaluation value in the component-based DSM while \(d_{\min}\) means the minimum one. For example, when there are a given matrix and its OCD as shown in Figure 6 (c), \(d_{\max}\) and \(d_{\min}\) are “2” and “-2”, respectively. Thus, using equations (2) and (3), \(S_1\) and \(S_2\) are calculated as follows.

\[
S_1 = O_{AB} + O_{AC} + O_{AD} + \cdots + O_{ED} = (0) + \left\{ \begin{array}{ll}
1 - \frac{1 - (-2)}{2 - (-2)} & \text{if } d'_{ij} = 1 \\
0 & \text{if } d'_{ij} = 0
\end{array} \right. = 3
\]

\[
S_2 = O_{AB} + O_{AC} + O_{AD} + \cdots + O_{ED} = \left\{ \begin{array}{ll}
2 - (-2) & \text{if } d'_{ij} = 1 \\
0 & \text{if } d'_{ij} = 0
\end{array} \right. = 7.5
\]
Equation (1) represents the three information content. The first term is the information content relating to the number of the clusters and the number of the components included in them, in order to evaluate the size of each cluster. The second and third terms are those relating to the mismatch between the given matrix and the OCD, in order to evaluate the similarity of them. Note that, α and β are the weights between the three information content (0 < α, 0 < β and 0 ≤ α + β ≤ 0), in order to balance all the terms.

3.3. Procedure of proposed method

The procedure of the proposed method is described in Figure 7.

STEP1: Arrange the product components in both the row and column of the component-based DSM and describe the evaluation values of the interactions between them.

STEP2: Calculate the integrated evaluation values on the basis of the rule of the integrated evaluation values to prioritize the positive one (Figure 4 (a)). This rule clusters not only the components including the positive evaluation values but also those including both the positive and negative values (i.e., trade-off relationships).

STEP3: Conduct the prior clustering using the integrated evaluation values calculated in STEP2.

STEP4: Calculate the integrated evaluation values on the basis of the rule of the integrated evaluation values to prioritize the negative one (Figure 5 (a)). This rule separates the components having the trade-off relationships (i.e., to identify the sub-clusters) in each cluster identified in STEP3.

STEP5: Conduct the latter clustering using the integrated evaluation values calculated in STEP4.

Figure 6. Conceptual drawing of Yu’s clustering algorithm [16, 17]

Figure 7. Procedure of proposed method
STEP2: Calculate the integrated evaluation values on the basis given matrix and the OCD, in order to evaluate the similarity third terms are those relating to the mismatch between the information content $0 < \alpha < 1$.

Equation (1) represents the three information content. The first

STEP1: Arrange the product components in both the row and column of the matrix. The second and the third terms are the matching and mismatch between the information content.

The interactions dealt in the previous illustrative example are the following three types: “performance (energy efficiency and operability)”, “space (adjacency of the components)”, “cost (economy)”. Ogawa’s method can satisfy the previous illustrative example because of the concept of the previous studies of M-QFD [2-4].

The interactions derived from the trade-off relationships are few. This study, therefore, increased the number of the interactions. In particular, this study assumed some optional functions mounted on the steering system (e.g., the energy-absorbing steering system and the steer-by-wire steering system) and clustered on the basis of the four interactions; “space”, “performance”, “cost”, and “safety (energy-absorbing characteristic)”. The arrangement of the product components and the evaluation values of the interactions between them were done by an automotive engineer.

4.2. Results and discussion

Figures 8 and 9 show the clustering results identified by Ogawa’s method and by the proposed method, respectively. In both figures, the bold black lines show the identified clusters. In Figure 9, the bold gray lines and the gray cells denote the sub-clusters and the trade-off relationships between the components, respectively, and the values of the upper left, the upper right, the left below, and the right below in a cell show the evaluation values regarding “space”, “performance”, “safety”, and “cost”, respectively. While, the values in the center mean the integrated evaluation values.

Figure 8 shows Ogawa’s method cannot properly identify the number of the clusters because all the components are included in a cluster. On the other hand, the proposed method identified the two clusters: the I/M shaft cluster and the R&P gear cluster (Figure 9). The former cluster were further classified into the two sub-clusters: the I/M shaft and the energy-absorbing mechanism components, while the latter cluster were further classified into the four sub-clusters: the R&P gear components, the electronic components (the assist

![Figure 8. Result of Ogawa’s method](image-url)
motor, the ECU, and the torque sensor), the wire harness, and the steering reaction force mechanism components.

Additionally, using the derived interactions of the trade-off relationships between the sub-clusters, the engineer considered some candidates of the cluster composition according to his expertise. One of the candidates is described below.

A candidate of the cluster composition focusing on “performance” is depicted in Figure 10. In this case, the sub-clusters of the column components and the steering reaction force mechanism components become one cluster; the sub-clusters of the R&P gear components and the electronic components become one cluster, because the evaluation values regarding “performance” between each sub-cluster are “+2”. This cluster composition suggests the designers to connect the column components and the R&P gear using the steering reaction force mechanism components and the wire harness (i.e. eliminating the mechanical connection), in order to decrease the vibration (i.e. to improve “performance”). Moreover, the eliminating suggests the enlargement of the tilt adjustment angle of the steering handle and corresponds

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**Figure 9. Result of proposed method**
clusters of the column components and the steering reaction motor, the ECU, and the torque sensor), the wire harness, and "performance"

Additionally, using the derived interactions of the trade-off reduction gear Shaft part -2 0 -2 0 -2 0 -2 0 -2 0 -2 0 -2 0 -2 0 -2 0 -2 -2 -2 2 -2 2 -2 2 -2 2 2 0 2 2 2 0 2 0 -2 2 -2 2 -2 2

Safety

This cluster composition suggests the designers to connect the regarding "performance" method

Figure 10. Candidate of cluster composition focusing on "performance"

Figure 11. Conceptual drawing of steer-by-wire steering system and tilt & telescopic steering system
diverse physiques of the drivers (i.e. to improve "performance"). This result implies the following two steering systems: the tilt & telescopic steering system and the steer-by-wire steering system (Figure 11). The former system mounts the tilt motor and the telescopic motor and can adjust the angle and the depth of the steering handle. Whereas, the latter system employs the wire harness instead of the I/M shaft and can be operated only by the electrical connection.

Therefore, compared to Ogawa's method, the proposed method can support designers to integrate or decompose the
components on the basis of the trade-off relationships and to organize the design ideas.

5. Conclusions

This study, to solve the problem: “it is difficult to assure the adequate number of the clusters due to become larger the components including each cluster”, reviewed the conventional clustering methods and proposed the clustering method for evaluating the trade-off relationships between the components. This method derives the sub-clusters in each cluster and locates the trade-off relationships out of them. This enables designers to integrate or decompose the clusters considering the trade-off relationships using their expertise. Additionally, the applicability of the proposed method was confirmed by the illustrative example of an automotive steering system design.

To confirm the versatility of the proposed method, in the future, we will implement it to other design applications.

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References