Modular Decomposition Method Based on Design Structure Matrix and Application

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Abstract

Modular decomposition is an effective means to achieve a complex system, but that of current part-component-based does not meet the needs of the positive development of the production. Design Structure Matrix (DSM) can simultaneously reflect the sequence, iteration, and feedback information, and express the parallel, sequential, and coupled relationship between DSM elements. This article, a modular decomposition method, named Design Structure Matrix Clustering modularize method, is proposed, concerned procedures are defined, based on sorting calculate and clustering analysis of DSM, according to the rules of rows exchanges and columns exchange with the same serial number. The purpose and effectiveness of DSM clustering modularize method are confirmed through case study of assembly and calibration system for the large equipment.

Keywords: modular decomposition, design structure matrix (DSM), cluster analysis

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1. Introduction

The decomposition can be described as a process that a product or system is divided into multiple sub-components to simplify the system and reduce the problem dimension. The decomposition is good to the realization of complex product system, whereas the modular decomposition is an effective means to achieve a complex system [1], as is using in many fields [2][3]. Many scholars have proposed many different decomposition methods from different angles based on existing component system such as Erixon [4], etc. proposed 11 conditions for a system function as an independent module. Based on this, the 11 conditions become general principles for module division, which can be used to establish the module identification matrix (MIM) and then do the cluster analysis for the various functional carriers. Stone [5] suggested a type of functional quantitative modeling method used for the product architecture development, which associates the various model functions with energy flow, logistics, and signal flow, and takes the customer need as a measure to establish the degree of customer demand and functional database. This method quantitates relationship between functions and needs, thus makes it as the main basis of the module division and module development. By analyzing the degree of interactions between the product components (functions) with the materials, energy, information, and space to determine the module division, reference [6] introduced an interaction matrix for this purpose. By analyzing the frequency of some kind of interaction between the product components to determine the module division, reference [7] mainly focused on the aspect of technology in module division. Reference [8] stressed that the technical and economic factors play an important role in the module division. Reference [9] proposed a module division method which comprehensively considers the MIM and relevance. To comprehensively consider the factors of market, production, and technology in module division, reference [10] proposed a three-dimensional relationship matrix method. To consider the versatility and reusability, reference [11] suggested a reusable matrix. In order to optimize the number of module variants, reference [12] introduced the robust design. GU [13] proposed a module division method that is product life cycle engineering multi-objective-oriented (easy recyclability, scalable, reusable, and reconstructible), which uses the weight of the concept of fuzzy mathematics to process the functional structure analysis, and, thus provides a basis for module division from qualitative to quantitative.
For the positive development of a product, because of the lack of complete component information, it is necessary to build product system from customer needs analysis and embodies information sequence, iteration and feedback. The use of DSM [14][15] can achieve such goal. DSM contains all composition of events and activities and information dependencies between activities and is a compact matrix representation and an effective tool for analyzing dependencies between activities. It is especially good for visual analysis of complex projects [16]. DSM was evolved from a directed graph in 1967, when Steward D.V. [17][18] was involved in the work of nuclear power plants and conceived the concept of the DSM, which was initially used for planning and analysis of the information flow in the product development process in 1981. In the 1990s, Eppinger S.D.[19][20] and Browning T.R[21][22] proposed a computation method for technical structure of the DSM model, which not only can reorder tasks, but also can simplify the task or break down into smaller tasks to avoid the bottlenecks of the process. This paper uses the DSM clustering algorithm for modular decomposition of the complex product system, and proposes modular processes and procedures with applications.

2. Research Method

2.1. DSM-Based Modular Decomposition

2.1.1. DSM and Classification

a. DSM Form

DSM reflects the interaction between similar elements in the form of N-order square matrix. Elements form a matrix with the same ordered sequence as the matrix rows and columns. There are three types of relationships between elements in a system such as parallel, serial, and coupling. Figure 1 shows using directed graph and DSM to represent the relationship between two elements and their corresponding functional relationships, as well as solving process.

![Figure 1. Element relations and Expression](image)

b. Numerical DSM

Binary DSM commonly uses "1" or "x" to mean a relationship existing and "0" or "space" for no relationship. Sometimes, the degree of association between different elements is different and this relationship needs to be reflected in the DSM so it is necessary to adopt the NDSM. The NDSM can contain a variety of attributes and provide detailed relationship between information and the key elements of different systems in order to better reflect the system properties.

The numerical values in numerical DSM represent the relevancy or the degree of importance. Steward D.V. [18] suggested that DSM do not use only a single "x" sign but the scale number. The range of scale numbers can be 1-9 determined by engineers according to the determined information level. The simple importance ratings can use a 1-3 to distinguish different levels of dependence: 1 = highly dependent, 2 = moderately dependent, and 3 = low dependent. Another method includes the use of positive and negative value such as -2, -1, space, 1, 2. They represent different meanings such as 2 for a highly coupled, 1 for the much low degree of coupling, a space for no coupling, and negative numbers for the system engineer’s ensuring that no coupling and the coupling of limited relative intensity.
c. Element Classification

The relationship between the matrix elements which represent DSM functional feature is different. Because the different relationships need different handling, so the elements in the DSM need classification in order to use different classification and evaluation methods for different types of elements. Based on clustering relationship of the respective elements, different elements can be divided into three categories: independent element, bus clustering elements, and ordinary clustering elements (short for clustering elements).

The independent element has no association or very little association with other elements. It independently exists in the entire product structure model and does not belong to any clusters. The completion of the independent elements is rarely affected by other elements, but rarely affects the completion of the other elements either, and thus can be completed parallel to the other elements.

The bus clustering element refers to the elements that have association with most of the other elements, which are similar to the bus in the computer interface technology\(^ {22,3} \), called the bus clustering elements. All bus clustering elements in a product DSMF model are composed of a bus cluster. The bus clustering elements in a product development would be completed by a team that the members are more familiar with each part of the entire product structure in order to better coordinate the relationship between the bus clustering elements and other elements, thus it is good for the integration team to control the completion of overall structure of the entire product.

The cluster elements are all other clustering elements other than bus cluster elements in product structure DSMF model.

2.1.2. DSM Calculation

a. Row and Column Transformation

The row and column transformation for a product structure DSM model is accomplished by multiple steps of exchanging element positions. Each step of exchanging position is to exchange positions between two target elements. To ensure that the order of row elements is consistent with the order of column elements after position exchange, and meanwhile to ensure that the relationship between row elements and column elements is not distorted before and after position exchange, it is necessary to simultaneously exchange the target element's row element and column element, that is, when exchanging the row elements, all cells in the columns of two target elements also will exchange, and when exchanging the column elements, all cells in the row of two target elements also will exchange.

b. DSM Sorting Calculation

Sorting is the most basic calculation for dependence structure matrix, and any other calculations are only carried out after the sorting calculation. Sort computing is to rearrange the positions of row and column elements in the matrix to eliminate the matrix loop as much as possible, which is a process that moves marks (or values) above the diagonal in the matrix to the location below diagonal. Sort calculation will help to obtain a smooth flow of information and thus try to ensure that the information needed by each task is obtained prior to execution of this task. The object-relational expression of the five elements DSM before and after the sort calculation is shown in Figure 2.

![Figure 2. Sorting calculation of design structure matrix](image-url)
c. DSM Cluster Calculation

The clustering is a process identifying and sub-blocking interdependent operations in the DSM matrix. The more elements are in the complex relationship matrix, the more complex relationships are between them, and the more difficult to deal with the matrix accordingly. Sometimes, there will be many coupling information in the sorted matrix as shown in Figure 3. However, the matrix can be divided into small blocks and the information relationship between elements is concentrated in the block so this process of operation identification and sub-blocking is called the cluster analysis.

\[\text{Input: } A \quad B \quad C \quad D \quad E \quad F \quad G \quad H \quad I\]

\[\text{Output: } I \quad E \quad B \quad C \quad D \quad F \quad A \quad G \quad H\]

\[\text{ figure 3 cluster calculation of dependence structure matrix}\]

2.1.3. Module division base on DSM clustering

Cluster of product function cell be founded with DSM calculation, and that corresponds to the function of nodes of product functional tree, to form the product DSM clustering tree. Figure 4 shown a product(named XXX) which consists of 6 function cells(C1, ..., C6), formed two parts by the DSM clustering calculated. Cluster 1 included C1 and C3, and cluster 2 included C2, C4, C5, and C6. Respectively, different cluster forms different module. The DSM model corresponds to the product structure tree shown in Figure 5.

\[\text{figure 4 DSM model of product XXX}\]

\[\text{figure 5 Cluster modular decomposition of product XXX}\]

It can be seen from Tab. 2 that there is no interaction information between the first block and the second block, and no interaction information between the second block and third block but the operation F is contained between the second block and third block. From the figure we can also see that dividing a big block into several small pieces makes the matrix operation simplified, intuitive, reducing the number of iterations, shortening the cycle, and improving the efficiency.

2.2. The Process of Clustering Module Division

The procedure of cluster division based on row and column transformation is as follow:

Step 1 : Weak Link Tearing
The different degree of association between the row elements and column elements has different degree of influence on the cluster division. To lower the degree of complexity of cluster division and prevent the undue influence of the weak link on the clustering results, it is necessary to temporarily make tearing process for those weak links before the cluster division (i.e., temporarily reduce the association strength of weak link to 0) and put the weak link back into the model after the completion of cluster division.

Step 2: Identification and Separation of Independent Elements
Check the product structure DSM model after the completion of weak link tearing, and locate elements of 0 cell values in row and column of the matrix, that is, independent elements. Because independent elements have no links with other row elements or column elements, there is no need for cluster division for independent elements. Therefore the independent elements and their cells can be temporarily removed. When the cluster division is completed, then the independent element can be added back to the row elements and column elements in the DSM model.

Step 3: Row and Column Transformation
Implement row and column transformation and make non-zero cell in the matrix close to model diagonal as much as possible.

Step 4: Identification of the Bus Class Element
Locate the bus class elements that have links with most of the other row elements and column elements. Move bus class element to the end of queue of row elements and column elements to form the bus cluster.

Step 5: Cluster Division and Row and Column Transformation
Divide non-bus class elements into several clusters based on the non-zero cell intensity in the DSM model from the previous 4 steps, and make the non-zero cells be included in the internal cluster as much as possible, as well as have the number of clusters reasonable.

Step 6: Put independent elements to the top of the queue of the row elements and column elements in the DSM model

Step 7: Add the torn weak link to the DSM model
The cluster division scheme based on cluster division method with the row and column transformation is often not unique, which can result a variety of divisions.

3. Case study
Assembly and calibration system is the facility to finish the process that Linear Replace Units (LRUs) assembling with mechanical components and of optical components transfer from assembly and calibration room with the cleanness of class 100 to the laser hall with the cleanness of class 10000, under keeping cleanness, and cleanly installed in the corresponding location of laser equipment with the cleanness of class 100, and to finish the reverse process, as is shown in Figure 6.
The function requirements of the assembly and calibration system includes assembly and calibration function, transportation function, clean closed loop, the precision of assembly and calibration, the efficiency of assembly and calibration and the space of assembly and calibration as constraint condition.

The assembly and calibration modular decomposition divides the general function into small modules, and at the same time the constraints also need to be decomposed to determine each module constraints and connection interface between each module as input conditions for solving module. The module functions, constraints, and interfaces are listed in the Tab. 1.

There is only boundary link between the modules (mainly to pass the supporting force) but no size coupling, electromechanical coupling, fluid-solid coupling, etc. There is only the interfaces connection between modules, and some modules have a space layout planning, that is, module three-dimensional size constraints. The relationship between the modules is shown in Figure 7.

<table>
<thead>
<tr>
<th>No.</th>
<th>Module Name</th>
<th>Function</th>
<th>Constraint</th>
<th>Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Lifting mechanism</td>
<td>Lifting function</td>
<td>Distance of travel, Load, Clean, Size</td>
<td>Boundary, Influenced by B deformation</td>
</tr>
<tr>
<td>B</td>
<td>Sealed frame</td>
<td>Sealed bearing</td>
<td>Seal, Deformation, Clean, Size</td>
<td>Boundary, Influenced by A deformation</td>
</tr>
<tr>
<td>C</td>
<td>Side door</td>
<td>Passage</td>
<td>Seal</td>
<td>Boundary</td>
</tr>
<tr>
<td>D</td>
<td>Top door</td>
<td>Upper and lower passage</td>
<td>Seal, No flip space</td>
<td>Boundary</td>
</tr>
<tr>
<td>E</td>
<td>Walk system</td>
<td>Walk straight or turning</td>
<td>Turning radius, Size</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Level adjustment unit</td>
<td>Cross movement</td>
<td>Load, Deformation, Size</td>
<td>Boundary, Influenced by H deformation</td>
</tr>
<tr>
<td>G</td>
<td>Plane adjustment unit</td>
<td>Lifting function</td>
<td>Load, Deformation, Size</td>
<td>Boundary, Influenced by H deformation</td>
</tr>
<tr>
<td>H</td>
<td>Support frame</td>
<td>Support pressure</td>
<td>Load, Deformation, Size</td>
<td>Interface with E, F, and G</td>
</tr>
</tbody>
</table>

Figure 7. Modules relation of assembly and calibration system

4. Conclusion

The decomposition is a common method to simplify the system and reduce the problem dimension. The modular decomposition is the most effective means. In order to solve the problem that the current modular decomposition based on component analysis does not meet the demand for product positive development, it is needed to combine the modular decomposition method of the product development process. DSM reflects the order of information and iteration and feedback at the same time is an appropriate tool to express the parallel, serial, and coupling relationship between the elements. Based on the DSM row and column algorithm, this paper realized module division by cluster analysis on the basis of sorting calculation. This paper also established the DSM clustering modular method and the clustering modular process and used them to implement the modular assembly and calibration system on large-scale laser device, which confirmed the value and effectiveness of the method.
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