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Multiple Perspectives, Hierarchical Module Division Method A Case Study

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Abstract: As the main way of realizing product diversification, modular design technology has been widely used in more and more industry. Module division method is the key to the modular design technology, reasonable and effective module division is of important significance for the entire product design and manufacturing, which has become a research focus at home and abroad. Module division is that according to the principles of module division, the product are divided into a number of basic units from different perspectives and finally the units are clustered as product module using clustering method. The purpose of this paper is to provide a new method of module division based on the multi-perspective and hierarchical characters in dividing a product into different modules. In this method products are divided into a series of functions units based on users' demand; then correlation matrix is defined according to the specific needs of the users, finally the functional units are clustered into modules, the division result is embodied in a hierarchy which is not referred in previous researches. A case study methodology was employed to gain insight on how the new method is achieved in Cabinet Office Furniture module division. The findings of the case study suggest that the validity and practicability of the module division method.

Key words: Modular design, module division method, hierarchical modularity, correlation matrix, cabinet furniture

INTRODUCTION

Modular design is the important design method and core technology of the adoption to the design and mass customization, through different combinations of functional modules it can achieve product customization and customized design, it has been widely used in machine tools, gear reducers, computers, household electrical appliances, furniture and other industries (Gu *et al*., 2004), in order to meet the increasingly widespread and rapidly changing market requirements, product developers should accelerate the speed of new product development and improve the flexibility of products as fast as possible. The purpose of modular design method is to use as little as possible the type and number of modules to integrate as many types and specifications of product as possible (Yanlin, 1993). For the purpose of the module division and classification, this paper proposes a multi-perspective hierarchical module division method. This method uses the users' needs as its foundation and a focused module division is conducted from many perspectives depending on the design intent. The result of division is expressed as a hierarchy.

The concept of Modular Design was formally proposed by a number of countries in Europe and America in the 1950s, it got more and more attention and research from then on. There are also many researches on the definition of the concept of modular design, realization process and module division, the planning and designing of product family based on the modular design and many other fields.

Ulrich and Tung (1991) studied the basic factors that impact the modular design from the design viewpoint: the degree of correspondence between functional domain and physical structure domain in design affects the degree of modularity; the mutual influence degree of the product physical structure is minimized. Suh (1990) defined modular design from the perspective of the mapping of the function-design parameter: modular design is a kind of analytical results generated by products, processes and systems in the form of performance and meets the predetermined requirements, the method is to select the appropriate design parameters, complete the mapping from functional requirements domain to the design parameters field. Pahl and Beitz (1996) considered that the modular design is the completion of the mapping from functional requirements domain to the module functional domain and then completes the mapping from module functional domains to the module structure domains based on the module performance, thus attains the

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corresponding module classification definition in the module functional domains and structure domains following the differences of module function. In the research on module division technology, Erixon *et al.* (1996) proposed 11 conditions which can make a sub-function as an independent module. This is used as a general module division principle, then module identification matrix is established, finally clusters the functional carriers. Gu and Sosale (1999) proposed a module division method which is used for multi-objective of Product Life Cycle (easy recycling, scalable and can be used repeatedly, reconstruction, etc.). The concept of fuzzy weights is used when analyzing functional structure which provides a basis for transformation from qualitative to quantitative in module division. Stone *et al.* (2000) proposed a quantitative modeling method of function model for product framework development. It makes various sub-functions in the model and energy flow, logistics and signal flow associated to measure the degree of customer demands, the requirements and functional database are established and the relationship between function and demand quantitative is made, which is the main basis for the module division and development of module. In the research on module combination technology, Tsai and Wang (1999) considered the complexity of design, fabrication and assembly from the viewpoint of concurrent engineering, he divided products into different types of modules following the function of their appearance in the design process, then chose the optimal module and schedule the priority of each function module according to the module information as a basis for planning and design. O'Grady and Liang (1998) studied the module integration methods under the environment of distribution network of collaborative design, it can quickly combine the modules from different places, different module manufacturers into modular products to meet customer needs through an object-oriented modular product design environment. The module interface matching is an important premise in the module integration. Hillstrom (1994) combined traditional DFMA methods and axiomatic design theory for analysis of modular interfaces.

MODULE DIVISION PERSPECTIVE

When product designers divide modules for different products, they should consider the specific users' needs from a different perspective. From the viewpoint of the product life cycle, these different division perspectives are for products at different stages of the lifecycle (Huang, 2000). Thus, according to the specific stages of the life cycle, the module division is classified as five kinds of module division: design-oriented module division; manufacture-oriented module division; assemble-oriented module division; use and maintain-oriented module division; recycle-oriented module division.

Common characteristics of different perspectives in module division: The common points of different perspectives on module division are: meeting users' demands as the ultimate goal; functioning well as the basis; structure as a carrier; strong coupling inside the module; loose coupling between modules. Different perspectives module division is characterized by: (1) When modularity is mainly for the design stage of the product life cycle, modular division is mainly based on the degree of function correlation between the products various components. (2)When modularity is mainly for the manufacturing stage of the product life cycle, the module division should focus on process issues. (3) When modularity is mainly for the use and assembly stages, this module division should focus on the handling and interface issues. (4) Module division for recycling stage should focus on materials and reusable components issue.

Selection of module division perspective: Market demand is the fundamental basis for selecting module division perspectives. When the demands for certain types of products in the market are more quickly to change, module division typically focuses on design. When demands change and changes should be made to the product design, you can only improve or replace the corresponding function modules, while retaining the rest of the original product. So, that you can make full use of existing design experience, shorten the development cycle of new products to enable enterprises to compete in a favorable position. If the market demand of product is relatively stable, while the manufacturing process is more complex, module division typically focuses on manufacture-oriented. This is benefit to the reasonable organization processing and manufacturing process, thus improving manufacturing efficiency and improving product quality. If the user requires frequent replacement or maintenance of certain parts of the product, product module division usually focuses on assembly and maintenance. By this way, according to the requirement of their own, users can easily replace or load and unload the relevant parts, thus improving efficiency. If the market requirement of the environmental performance of the product is higher, module division typically focuses on recycle-oriented. This is conducive to put the polluting material or recycled materials in one module, facilitating recycling and processing. For the current advocate of green products, module division in this perspective is of more practical significance. When designers perform the product module division, they usually take multiple perspectives into account. The module division resulting solution may be conflicting at different perspectives, which needs designers consider trade-offs carefully to get the final result (Gu and Sosale, 1999).

GRADING CHARACTERISTICS OF MODULE DIVISION

Grading characteristics of product itself: Module division possesses the hierarchical nature, which is determined by the characteristics of the product itself (Tu, 1994). For general products, especially products of complex structure, they possess a hierarchical character in functional and structural characteristics. Therefore, describing the product composition of the module should also reflect hierarchy. The product in Fig. 1 consists of certain senior modules and an advanced module may consist of several lower-level modules. For example, Module 2 consists of three lower modules they are Module 21, Module 22, Module 23.

Characteristics of different levels of module division: (1) The division angle of different module levels. When dividing the higher-level modules, as these advanced modules are often directly selected and replaced by the users, module division often focuses on the design and use angles; when performing division of the lower-level module, due to the low-level modules and components are similar (some lower module may be even a component), it should focus on the perspective of manufacturing and assembly. (2) The correlation of function and structure of different levels of product module reflects certain corresponding relationship between function and structure. The lower the level of the module is, or the more finely modules are divided, the simpler and clearer the correspondence between the function and structure is.

MULTI-PERSPECTIVE, GRADING MODULE DIVISION METHOD

Functional decomposition: The functional requirements of the product are decomposed top-down until every sub-functions can be controlled by a separate structure to achieve. This sub-function is called the functional unit. Functional unit is the basic element for modular division. Each module consists of one or several functional units. In Fig. 2, FR represents the total product functional requirement, it can be decomposed into three sub-functions, they are: FR1, FR2 and FR3. FR2 can be decomposed into two sub-functions, they are: FR21 and FR22. FR1, FR21, FR22, FR3 are functional units.

Definition of correlation matrix (Jiang *et al.*,1999): The degree of association is as following: Functional correlation is $r(FR_i, FR_j)^{(F)}$; manufacturing related degree is $r(FR_i, FR_j)^{(A)}$; assembly/use correlation is $r(FR_i, Fr_j)^{(A)}$. There are also maintenance-related degrees; recycling and other related degrees.

It should have the following properties whatever the correlation is:

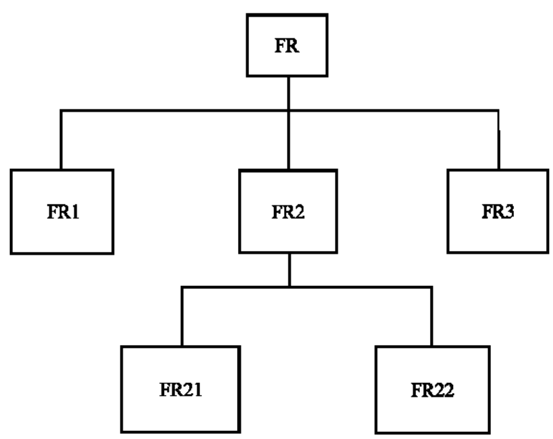

Fig. 2: Diagram of functional division

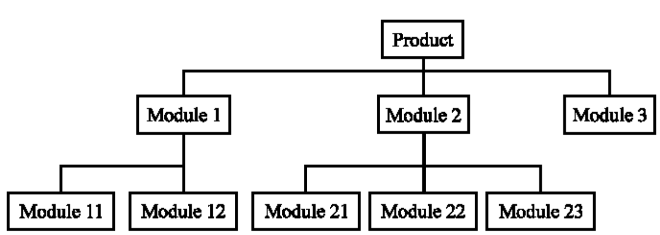

Fig. 1: Diagram of hierarchical division

$$r(FR_i, FR_i) = 1; r(FR_i, FR_j) = r(FR_j, FR_i); \quad r(FR_i, FR_j) \in [0,1] \quad (1)$$

Computing device of function correlation : Hypothesis the distance of FR_i and FR_j to the nearest public parent function are i_i and l_j, command:

$$x = \frac{1}{2^{li+lj-2}}$$

$$r(FR_i, FR_j)^{(F)} = \begin{cases} x & x \geq 0.25 \\ 0 & x < 0.25 \end{cases} \quad (2)$$

The l_i, $l_j$are the progressions of Fr_i and Fr_j to the nearest common parent function. For example the distance of $FR_{21}$to $FR_2$is 1 and the distance of Fr_{21} to FR is 2.

Computation of manufacturing related degree : When the function units FR_i and Fr_j are suitable for a group of independent processing, its manufacturing relevance is $r\ (FR_i,\ Fr_j)^{(M)} = 0.6$.

When the function units FR_i and FR_j are suitable for testing together, its manufacturing correlation is $r\ (FR_i,\ Fr_j)^{(M)} = 0.4$.

When the function units FR_i and FR_j are suitable for both of the above conditions, its manufacturing correlation is $r\ (FR_i,\ Fr_j)^{(M)} = 1$.

Assembly/use correlation calculations: When the function units FR_i and FR_j present permanent assembly relationship in the product, after the assembly they will not separate (they can be simultaneous removed) until the product retirement. Then the assembly/use relevant degree is $r\ (FR_i,\ Fr_j)^{(A)} = 1$.

When the function units FR_i and FR_j may exist assembly relationship in the product, but both may occasionally be isolated in the assembly/use processes, then the assembly/using relevant degree is $r\ (FR_i,\ Fr_j)^{(A)} = 0.5$.

When the function units FR_i and FR_j may exist assembly relationship in the product, but both can be often separated in assembly, then the assembly/using correlation is $r\ (FR_i,\ Fr_j)^{(A)} = 0.25$.

When the function units FR_i and FR_j do not exist assembly relationship in the product, the assembly/using relevant degree is $r\ (FR_i,\ Fr_j)^{(A)} = 0$.

Correlation matrix: The form of the correlation matrix is:

$$T = \{r_{ij}\}_{n \times n}, r_{ij} = r(FR_i, FR_j)$$

Depending on the different types of correlation, you can define different correlation matrixes. The author defines and uses three kinds of correlation matrixes, namely functional correlation matrix $T^{(F)}$, manufacturing correlation matrix $T^{(M)}$, assembly and using correlation matrix $T^{(A)}$.

Users determine the degree of importance of the three kinds of correlation from their own actual situation and assign them weight coefficient $\omega^{(F)}$, $\omega^{(M)}$, $\omega^{(A)} = 1$, which make $\omega^{(F)}$, $\omega^{(M)}$, $\omega^{(A)} \in (0, 1)$.

So, that we attain the overall availability of integrated multiple perspective correlation matrix:

$$T = \omega^{(F)}T^{(F)} + \omega^{(M)}T^{(M)} + \omega^{(A)}T^{(A)} \quad (3)$$

If you want to introduce more types of correlation, just get the correlation matrix of various types, the overall correlation matrix can be obtained by the above method.

The ω can be specified directly by the user based on experience, can also be based on experience using the analytic hierarchy process.

First merger of function units: Take the threshold value of the overall matrix T as λ, the threshold value, then the threshold matrix of T is T*. The a_{ij} is the unit of T* which is in line i and column j:

$$a_{ij} = \begin{cases} 0 & rij < \lambda \\ 1 & rij \geq \lambda \end{cases} \quad (4)$$

When $a_{ij} = 1$, indicating that the correlation of FR_i and FR_j has reached a predetermined level, the two should be assigned to the same module. From the perspective of fuzzy mathematics, T* is not fuzzy equivalence relation matrix, so if you want to directly make module division according to T*, in addition to considering the direct relationship expressed by T* you should also consider indirect relations. For example, when $a_{ik} = 1$, $a_{jk} = 1$ but $a_{ij} = 1$, although the direct relationship of functional elements FR_i and FR_j is not enough to be incorporated into the same module, but they obtain an indirect relationship by function unit FR_k which requires both to be assigned to the same module, hence in the actual division the FR_i and FR_j should be assigned to the same module. Alternatively, you can first calculate the fuzzy equivalent matrix of T* and then do the consolidation of functional units according to the matrix. One-level module division program is obtained by the above method. Suppose that the final product is divided intol modules and M_i represents module i.Then:

$$M_i = \{FR_{i1}, FR_{i2}, \cdots, FR_{isi}\}, \sum_{i=1}^{1} si = n$$

The second merge of functional units. After carrying out a merger of functional element, you may think the number of modules is too big, while the obtained modules can be used as new functional units for secondary merge using the same method. The key issue is how to obtain the correlation matrix for the new module through the original functional element.

Suppose that both of M_i and M_j are modules obtained by the first merge of functional units. M_i = (FR_{i1}, FR_{i2},..., FR_{isi}), M_j = (FR_{j1}, Fr_{j2},..., Fr_{jsj}) the correlation of M_i and M_j is determined by the maximum correlation between all of the functional elements of M_i and all the features of M_j. Therefore, set r(M_i, M_j) = max (r(FR_{ix}, Fr_{jy}), x = 1, 2,..., s_i, y = 1, 2,..., s_j. Suppose:

$$C = \{FR_{c1}, FR_{c2}, \cdots, FR_{cp}\}$$

$$D = \{FR_{d1}, FR_{d2}, \cdots, FR_{dq}\}$$

are two function units meeting the conditions of the merger, then let us prove the above proposition logically. Command:

$$r_{max} = \max\left[r(FR_{cx}, FR_{dy})\right] = r(FR_{an}, FR_{dn})$$
$$x = 1, 2, \cdots, c_p; y = 1, 2, \cdots, d_q$$

When $r_{max} \geq \lambda$, since all the functional units of C meet the combination conditions, therefore, there is at least a direct or indirect relationship between any one element in C and Fr_{dn} so that the two should be assigned to the same module. And because all units of D should be grouped into one module. So, all functional units of C and D should be grouped into one module. When $r_{max} \geq \lambda$, it is easy to know that the direct or indirect degree between any two functional units of C and D is less thanλ, so the two can not be assigned to the same module. Therefore, all units of C and D should be classified into the same module, if and only if $r_{max} \geq \lambda$.

Multiple merge of functional units: After two times merger, the resulting number of modules is still too big, then you can continue merge the results after two merges until the number of modules satisfies the designer. In general, the final combined result should make the product contains no more than 9 modules. It is the maximum value for general people handling the affairs (Fixson, 2001). Usually controlling the modules at 7 around is quite reasonable.

CASE STUDY

Module division: Take office cabinet for example using the multiple perspectives, hierarchical module division method, first function division is made, then the module division is obtained.

- **Functional decomposition:** Office cabinet is decomposed by its function according to user needs, the result is shown in Fig. 3
- **Functional units include:** FR11, FR121, FR122, FR123, FR121, FR2, FR321, FR322, FR323, FR331, FR332, FR333
- The calculation of function correlation matrix $T^{(F)}$
- The calculation of assembly correlation matrix $T^{(A)}$
- The calculation of the overall correlation matrix

Take two kinds of correlation weighting for comparison, called program (I) and program (II).

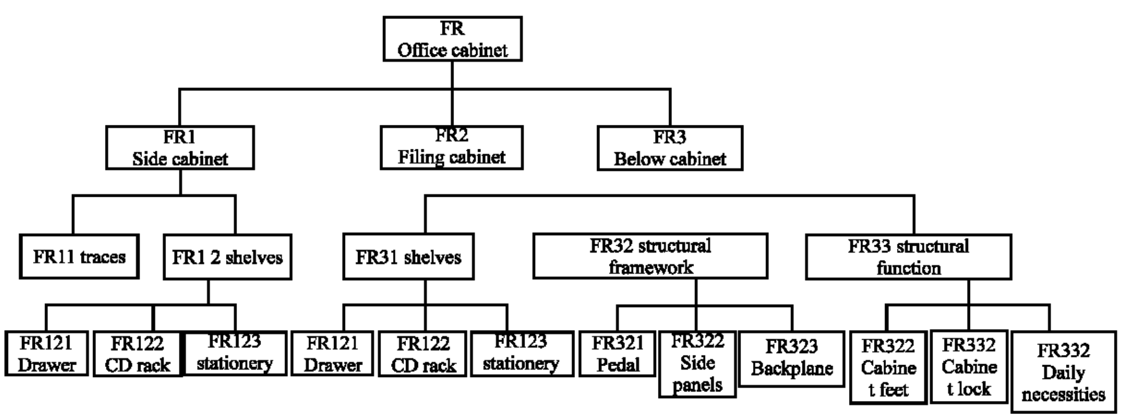

Fig. 3: Function division of office cabinet

(I) Take $\omega^{(F)} = 0.6$, $\omega^{(M)} = 0$, $\omega^{(A)} = 0.4$, the overall correlation matrix is $T_1 = 0.6T^{(F)} + 0T^{(M)} + 0.4T^{(A)}$, take $\lambda = 0.6$, obtain cross-sectional matrix T_1^*.

(II) Then take $\omega^{(F)} = 0.4, \omega^{(M)} = 0, \omega^{(A)} = 0.6$, recalculate the overall correlation matrix $T_1' = 0.4T^{(F)} + 0T^{(M)} + 0.6T^{(A)}$, still take $\lambda = 0.6$, obtain cross-sectional matrix $T_1^{*'}$

First merger of function units : Conduct a combination of the functional units according to truncated matrix T_1^* to get the module division result:

$$M_1^{(1)'} = \{FR_{11}\}$$
$$M_2^{(1)'} = \{FR_{121}, FR_{122}, FR_{123}\}$$
$$M_3^{(1)'} = \{FR_{321}, FR_{322}, FR_{323}\}$$
$$M_4^{(1)'} = \{FR_{331}, FR_{332}, FR_{333}\}$$
$$M_5^{(1)'} = \{FR_2\}$$

Result analysis: Module $M_1^{(1)'}$ corresponds to cupboard outer frame; module $M_2^{(1)'}$ corresponds to drawer module; $M_3^{(1)'}$ corresponds to the interface module; $M_4^{(1)'}$ corresponds to the decoration module; $M_5^{(1)'}$ corresponds to file cabinet module. The result of the module division is basically the same with the actual result.

CONCLUSION

In this study the multiple perspectives, hierarchical module division method has been introduced. The results from the case study of cabinet furniture show that the new module division method is correct and practical. Module division is an important step to achieve product modularity. Different users will get different results from different perspectives of module division.

Therefore, in the module division process the division's specific intent should be taken into account to make the results more adapted to the actual needs of users. Final solution obtained by the division is usually embodied in the hierarchical classification results, which is determined by the characteristics of the product itself. When module division is for different levels of the same product, division angles tend to change in the division process so this change should be taken into account.

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