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Procedia CIRP 53 (2016) 21 – 28

www.elsevier.com/locate/procedia

The 10th International Conference on Axiomatic Design, ICAD 2016

A systematic approach to coupling disposal of product family design (part 1): methodology

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Abstract

In this paper, on the basis of comparison and analysis on the similarities and differences of design coupling between product family and single product, a systematic approach to coupling disposal of product family design is proposed, and coupling disposal flow of two level including strategy level and operation level is given. From strategy level of platform plan, axiomatic design theory is utilized as framework to analyze and classify functional requirements, design parameters are mapped with "zigzagging" mode, and platform parameters are identified. In the view of platform operation level, design structure matrix (DSM) converted by design matrix DSM are clustered and grouped into modules, and coupling correlation matrix of product family design is established, which can realize high cohesion degree in a single module and low coupling degree among all the modules. Then, from the coupling inside platform modules, inside customization modules, and among design parameters with different modules, the corresponding decoupling methods of product family design are presented, and the methods architecture of to coupling disposal of product family design is established.

Peer-review under responsibility of the scientific committee of The 10th International Conference on Axiomatic Design

Keywords: product family, coupled design, coupling disposal, decoupling

1. Introduction

With the users' increasing demands for product customization and the rapid development of information technology, Mass Customization has recently received a significant amount of attentions within the business community [1]. Product family development has been widely recognized as an effective way to implement mass customization [2]. A product family is a group of related products based on the same product platform by providing a variety of products for achieving the economy of scale and accommodating the proliferation of customized product variants across different market segments. Platform-based product family design is an effective means not only to capture total cost savings and speed time to market but also to maintain differentiation and competitiveness. However, the design of a product family is typically more challenging than designing single product.

In regard to the design of product families, many literatures have been published during the last decades. A variety of methods and tools have been extensively developed to support product family design. Simpson [3] as well as Jose and Tollenaere [4] provided comprehensive state-of-the-art reviews of modular design, product family design and platform-based product development. Kumar et al. [5] proposed a methodology to design product families integrating market considerations to examine the impact of increasing the product variety. Barajas and Agard [6] proposed a comprehensive methodology to form product families by taking advantage of the fuzzy logic to tackle uncertainties. Eichstetter et al. [7] presented an approach to identify components in order to optimize commonality for a product family of arbitrary high-dimensional nonlinear systems.

Peer-review under responsibility of the scientific committee of The 10th International Conference on Axiomatic Design
doi:10.1016/j.procir.2016.07.064

There exist generally relationships between product variants in product family that cause physical coupling between product platforms and it will increase the difficulty of product design. Thus the coupling should be avoided to the greatest extent. But in the actual product design, due to technical or other limitations, it is very difficult to get uncoupled design or decoupled design. Therefore, coupling problem in product design has become one of the key problems to be solved urgently in engineering and industry fields. Chen and Teng [8] introduced the concept and description methods of product design coupling, elaborated the coupling analysis method which was commonly used at present and its application in product design, and discussed the comparison of the studies on direct coupling and coupling propagation and the existing problems.

Independence axiom in Axiomatic Design (AD) theory provided the fundamental criterion to judge whether the design is success or not and its improvement directions [9]. For example, Johannesson [10] defined coupling function as mutual negative effect between two subsystems while implementing a functional requirement. Kang [11] proposed using TRIZ conflict matrix into axiomatic design, choosing appropriate invention principle to decouple the coupling in axiomatic design. Choi and Hwang [12] proposed to represent the system structure using the flow chart, taking axiomatic design matrix as nonlinear, and then analysis the coupling relationship between the various modules. Su et al [13] used the split algorithm to rearrange the design matrix, measured the function coupling through analytic hierarchy process, and searched the optimum and initial iteration sequence of coupling function through optimization algorithm. Lee [14] comprehensive considered the costs and benefits of removing nondiagonal elements in the design matrix and achieved decoupling by determining the minimum sequence nondiagonal elements. Based on the design association, redesign division and mode selection, Chen et al. [15] analyzed the product internal coupling relationship and put forward the decomposition coupling design methods so as to realize the rapid redesign to support the product agile manufacturing. Cao et al. [16] proposed the structured coupling design method based on the independence axiom, using decomposition operation to identify the independent function and the coupling function sets, applying the pairwise comparison method and triangular fuzzy number to measure coupling function. Yu et al. [17] based on the network analysis method to study the interactions between functional requirements in axiomatic design, and put forward the evaluation algorithm in interaction and discriminated method to determine whether the interaction could be ignored. Cai et al. [18] used the axiomatic design theory to identify the coupling function while planning the design matrix, adopted systematic innovative thinking mode to describe the coupling problems, selected and applied innovative thinking motivation techniques to completely decouple the associated functional requirements. They also defined the concept of "fuzzy independent range", put forward a decoupling method based on satisfaction, decoupling design those coupling design that violation the independence axiom according to the satisfaction degree and the fuzzy independent range [19].

The above researches mainly focus on the coupling design problems of single product and used the explicit way of product design decoupling. This paper aims at the problem that the product family design is unable to complete decoupling, and discusses how to deal with physical coupling design problem. This paper mainly studies the coupling disposal strategy and decoupling methods in product family design.

2. Coupling analysis and processing in product family design

For single product design, from the perspective of product functionality - parameter, the coupling problem can be divided into two categories: functional coupling and physical coupling. For functional coupling, we can use the independence axiom, guided by the "zigzagging" mapping process in the adjacent domain of AD framework, to decompose FRs and adjust the design matrix, and reveal the interaction between FRs and DPs to identify independent design tasks and coupling design tasks. The functional coupling is disposed by this way. For physical coupling that is also called parameter association, we can use the Directed Graph, CMP (Critical Path Method), PERT (Program Evaluation and Review Technique), IDEF (Integrated Definition Methods), Petri nets, DSM (Design Structure Matrix) or other methods for coupling analysis and decoupling. Especially DSM method is widely used, and it may make the design task achieve the sequence optimization of design tasks [20]. In product design, there are two ways to deal with coupling problems: one is the split method, and the other is internal iteration method [21]. Therefore, design coupling problem of single product mainly determine the parameters or the properties of the task or iterative sequence from micro level, and can be used in customize design as well as innovation design, to improve the design efficiency and reduce the design complexity.

Product family refers to a group or a series of products. It is suitable to adaptability design of the product, and mainly consists of modular design and parametric design. The purpose is to improve and modify the existing products. Product family design is based on common platform and derives series of products. Common platform parameters reflect the universalities of product platform, and individual parameters reflect the differences of product platform. Generality and difference of product platform is a pair of contradictions. The more common platform parameters, the better platform generality, the lower design cost, but the customization ability will become poorer and can't fully meet customers' diverse demands. The less common platform parameters, the lager platform diversity, the easier to satisfy the customized needs, but the generality will become less and design costs will increase.

In both modular and parametric product family, the design coupling not only has the characteristics of single product design, but also takes the relationship between product variants in product family into consideration. Overall, there may be coupling relationship between parameters in product family design, and there exist association relationship and master-slave relationship between common platform parameters and individual parameter. Since common platform parameters cannot depend on the individual parameters, and the individual parameters cannot affect the basic functional requirements, this is a one-way relationship. If the master-slave and correlation relationships between individual parameters and common platform parameters are ignore, it is difficult to accurately describe the nature of product family coupling problems.

Product platform planning is design for product family and also follows the general laws of product design. According to the AD principle [9], uncoupling design is the most satisfied in any product design. However, in actual product design, completely uncoupling design is rare. Most product design is more or less coupling, just different in the coupling degree. Product family design is no exception, but according to the means and characteristics, the coupling between platform parameters and non-platform parameters should be avoided. Strong association parameters are not suitable to be platform parameters. Platform parameters can have a weak effect on the non-platform parameters but non-platform parameters cannot have a feedback effect on platform parameters, that's to say the influence is one-way.

Product family design includes both product platform design and member's design of product family. Product platform design measures the product family optimality from a macro level, while a single product design is a special design case in product family under the constraints and overall goal. It mainly considers the technical optimization with "design parameter". The coupling processing of product family design includes strategy level and operation level. Based on the viewpoint of platform strategy level, we mainly consider the user demand response, function demand analysis and modeling and the platform flexible planning under the market segmentation framework. Based on the viewpoint of platform operation level, we mainly trade off the generality and difference of product platform, cluster design parameters and determine the optimal values of design parameters, so as to improve the robustness of product family design and reduce the coupling in design. The coupling process of product family design stated above is shown in Fig. 1.

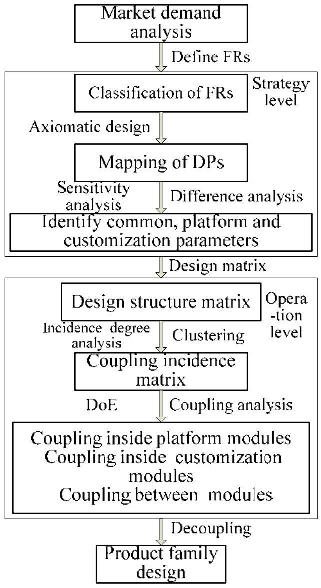

Fig. 1. The coupling disposal flowchart of product family design.

3. Coupling disposal of product family design on strategy level

Functional requirement analysis is very important in early product family design. Suitable requirements modeling can reduce the design coupling, shorten the product development cycle, enhance the robustness and improve the adaptability of product family design. Therefore, we should early plan related design activities and organizations, analysis the relationship between product design parameters and the type of functional requirements, to set up functional requirements model reasonably.

According to Xiao et al. [22], we may divide functional requirements of the product into basic functional requirements, expectable functional requirements and additional functional requirements. The division of functional requirement types can help to analyze the coupling relation of product family better. Each product variant should meet the basic function requirements of product family and then satisfy expectable functional requirements and additional functional requirements. Such a classification way of functional requirements can better determine the structure of product platform, the composition of product family and the relationship between family members. But it may lead to too little customization parameters and too many platform parameters, and can only use as preliminary coupling analysis of product family design.

Assuming the number of functional requirements is n. The basic functional requirements, expectable functional requirements and additional functional requirements are expressed in $\mathbf{FR}^b$、$\mathbf{FR}^e$、$\mathbf{FR}^a$ respectively. Then functional requirements $\mathbf{FR} = \{\mathbf{FR}^b, \mathbf{FR}^e, \mathbf{FR}^a\}^{\mathrm{T}} = \{FR_1, FR_2, \cdots, FR_n\}^{\mathrm{T}}$. Accordingly, the design parameter $\mathbf{DP} = \{DP_1, DP_2, \cdots, DP_n\}^{\mathrm{T}}$, $\mathbf{DP}$ decide the main characteristic parameters and structure design parameters set of functional requirements characteristics in product family. The relationship between design parameters and function requirements can be written as

$$\begin{pmatrix}\mathbf{FR}^b\\ \mathbf{FR}^e\\ \mathbf{FR}^a\end{pmatrix} = \left(\begin{array}{c} FR_1\\ \vdots \\ FR_u \\ \hline FR_{u+1}\\ \vdots\\ FR_{u+v}\\ \hline FR_{u+v+1}\\ \vdots \\ FR_n\end{array}\right) = \begin{pmatrix} A_{11} & \dots & A_{1n}\\ \vdots & & \vdots\\ A_{u1} & & A_{u,n}\\ A_{u+1,1} & & A_{u+1,n}\\ \vdots & & \vdots\\ A_{u+v,1} & & A_{u+v,n}\\ A_{u+v+1,1} & & A_{u+v+1,n}\\ \vdots & & \vdots\\ A_{n1} & \dots & A_{nn}\end{pmatrix}\begin{pmatrix} DP_1\\ \vdots\\ DP_u\\ DP_{u+1}\\ \vdots\\ DP_{u+v}\\ DP_{u+v+1}\\ \vdots\\ DP_n\end{pmatrix} \qquad (1)$$

From the view of satisfying customers' demands, each DP corresponds to one FR of the product. Design parameters that realize the basic or expectable functions of product family are defined as common parameters and platform parameters. Those realize additional functional requirements are defined as custom parameters. $\mathbf{D}_c$, $\mathbf{D}_p$ and $\mathbf{D}_r$ represent u common parameters, v platform parameters and w custom parameters respectively ($u+v+w=n$), $\mathbf{DP}=\{\boldsymbol{D}_c, \boldsymbol{D}_p, \boldsymbol{D}_r\}^{\mathrm{T}}$. We can get series of products depends on different values of n design parameters, in which the first $p+q$ have the common topology structure and have less or even ignored effect on product function. Their values are similar or within a certain scope between different product variants within a given product family, they are common platform parameters and make up the matrix of product family. Since the basic functional requirements of each product variant in the product family are the same, according to relationship between FRs and DPs and characteristics analysis of the product family platform, basic functional requirements are just affected by common parameters and should not be affected by other design parameters, and common parameters do not depend on other design parameters. That is

$$\frac{\partial FR_i^b}{\partial DP_j^{v+w}}=0,\ i=1,2,\cdots,u;\ j=u+1,u+2,\cdots,n \tag{2}$$

$$\frac{\partial \mathbf{D}_{ci}}{\partial DP_j^{v+w}}=0,\ i=1,2,\cdots,u;\ j=u+1,u+2,\cdots,n \tag{3}$$

Similarly, platform parameters are shared by product family members and should avoid coupling with custom parameters, its corresponding functional requirements would not be affected by custom parameters. That is

$$\frac{\partial FR_{\mathrm{i}}^{\mathrm{e}}}{\partial DP_j^{w}}=0,\ i=1,2,\cdots,v;\ j=u+v+1,p+2,\cdots,n \tag{4}$$

$$\frac{\partial \mathbf{D}_{pi}}{\partial DP_j^{w}}=0,\ i=1,2,\cdots,v;\ j=u+v+1,u+v+2,\cdots,n \tag{5}$$

When a functional requirement FR_i has changed due to customers' individual requirement, the corresponding design parameter DP_i should adjust to satisfy this functional requirements. At the same time, the non-corresponding design parameters （DP_j，$j\neq i$） may also change to eliminate the influence of DP_i changed. The greater ratio of DP_i changed with **DP** changed, the smaller affect of this parameter on the other design parameters, product variant is relatively easier, the design parameters adaptability is better. Obviously, in the product family design, non-coupling design parameters are more flexibility, and are more suitable for mass customization.

When product family design has satisfied independence axiom, it is effective and easy to be implemented to use formula (2) ~ formula (5) to identify the common platform parameters. But in general, there is the coupling in design which makes it difficult to meet all the equations above, thus lead to too less common platform parameters. We can consider the difference between product variants at this time. In product family design, whether product variants have in common with a certain product design parameter can be considered in terms of diversity. Assuming in a product family, the design parameters DP_i of two product variants A and B is similar, their values are $U(DP_i^A)$ and $U(DP_i^B)$ respectively. Then, the difference degree of these two design parameter values can be calculated by the following formula

$$d_{AB}(DP_i)=\frac{\left|U(DP_i^A)-U(DP_i^B)\right|}{\max\left(U(DP_i^A),U(DP_i^B)\right)} \tag{6}$$

Difference degree matrix of m products sets up by the difference degree of design parameter DP_i can be expressed as

$$\mathbf{D}(DP_i)=\begin{bmatrix} 0 & d_{12}(DP_i) & \cdots & d_{1m}(DP_i) \\ d_{21}(DP_i) & 0 & \cdots & d_{2m}(DP_i) \\ \vdots & \vdots & & \vdots \\ d_{m1}(DP_i) & d_{m2}(DP_i) & \cdots & 0 \end{bmatrix} \tag{7}$$

Difference degree matrix $\mathbf{D}(DP_i)$ shows the difference degree of product variants in one product family about a design parameter. The smaller difference degree about one design parameter, the less sensitive of this design parameter, and is more suitable to be a platform parameter.

Through the above discussion on functional requirements, we can plan platform design activities reasonably based on the coupling relationship analysis between three types of functional requirements, thus support for the choice of platform parameters, and reduce the coupling of product family design from strategy aspect.

4. Product family decoupling design based on coupling correlation matrix

4.1. Coupling correlation parameters analysis in product family

Once platform parameters of product family are determined, design matrix obtained by AD can be converted to DSM. Then we can reconstruct design structure matrix. Firstly DSM is divided into two parts, one is design parameters about common platform, and another is individual parameters oriented to individual demands of the customers. Secondly clustering algorithm is used to cluster and generate the clustering modules so as to make the cohesive degree within the modules as high as possible and the coupling between modules as low as possible. Finally, the coupling between modules is analyzed to find a kind of design with least coupling association between design parameters. In this way, the product structure is divided into several coupling modules with smaller dependence. The resulting matrix is called the coupling correlation matrix of product family design, as shown in Fig. 2.

The objective of clustering modules in DSM is high cohesion degree in a single module and low coupling degree among all the modules. The relationship between design parameters relies on the design team's experience and knowledge. Through the analysis of design parameters on functional relevance, connection relevance, physical relevance and so on, we can calculate the comprehensive relevance degree between design parameters.

	DP	D_c+D_p										D_r				
		1	4	2	3	5	7	6	8	9	10	12	11	13	14	15
D_c+D_p	1	1														
	4		1													
	2		1	1												
	3				1											
	5				1	1										
	7		①		1	1	1									
	6		↑				1	1								
	8		*A*	*B*	→	①			1							
	9								1	1	1					
	10									1	1					
D_r	12											1				
	11												1			
	13						*C*	→	①				1	1		
	14					*D*	→	①							1	1
	15											*E*	→	①	1	1

Fig. 2. Coupling correlation matrix of product family design.

In coupling correlation matrix of product family design, each element out of modules means modules are related, as shown in Fig. 2 with ring sign, makes various modules can't be completely independent, which is coupling, and affects the adaptability of product family design. According to the coupling correlation matrix, we can determine all association elements *A*, *B*, *C*, *D* and *E* between modules and conduct a test with them. They can be considered as controllable factors in parameter design, and their impact on the target are analyzed to implement control and adjustment, thus improve the robustness of product family design and reduce the coupling.

In experimental design of coupling correlation parameters, firstly we consider the influence of the upper-left parameters, which is association elements in the common platform module (such as *A* and *B*). Especially when there are common parameters which are association parameters at the same time (such as A), we should determine their impact on the other modules, since common parameters are shared in product family and can only change within a certain range, their change might cause the architecture change in product family. Secondly we analyze the information communicate relationships of correlation parameters in lower-left design parameters (such as *C* and *D*) to individual parameters, to make individual parameters be adapted to the changes of common platform parameters. Finally we consider the association parameters within individual parameters (such as *E*), since individual parameters can't feedback to the common platform, which is the primary difference between a single product design and product family design.

4.2. Processing method for product family design coupling

Product family coupling not only affect a single product, but might also affect all the designs of family members. Since the platform is shared, products topology should remain the same, and function structure, organization behavior and parameters specification are allowed to vary within a certain range. The platform structure should have certain adaptability and have no or weak coupling relation with non-platform structure and one-way influence it. Coupling relation design of product family includes three parts, one is internal coupling of common platform modules (hereinafter referred as platform module), the second is internal coupling of customization modules, and the third is the coupling association of design parameters between modules. For these three coupling relations, we analyze respectively and propose corresponding methods to deal with coupling below.

4.2.1 The coupling inside platform module

The coupling inside platform module should be given priority to, since it would affect the two coupling conditions behind. Common platform is equal to basic product in product family, its topology structure has been fixed (regardless of the platform upgrading and extension) and functional domains remain the same, but the intensity or size of functional requirements may change within a certain specifications by adjusting the corresponding parameter. Processing methods of coupling inside platform module is similar to that of the general coupling relation of product design, so we can reference to the related decoupling method which can be specific stated as follows.

Reselect design parameters or integrate multiple design parameters into a physical part to reduce the influence between design parameters, thus reduce the possibility of generating coupling relations in the design. This is the most effective and preferred method to reduce the coupling. We consider other decoupling method only when this method is difficult to achieve.

Choose the corresponding key DP corresponding to FR. Non-corresponding DP has small effect on FR. That's to say, FR shouldn't be sensitive to design parameters except the key design parameter. For a $n \times n$ coupling module, key design parameter DP_{ic} chosen by functional requirement FR_i should satisfy the following conditions

$$\frac{\partial FR_i}{\partial DP_{ic}} \Delta DP_{ic} > \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{\partial FR_i}{\partial DP_j} \Delta DP_j \quad i = 1, 2, \cdots, n \tag{8}$$

The module is weak coupling if it meets formula (8), otherwise it is a strong coupling. Weak coupling conditions can be considered to be essence decoupled and make it possible to design in the case of less interaction, which can simplified the problem so as to reduce the iteration and shorten the design cycle.

For strong coupling, since the common platform is just the substrate of product family, design target and constraints can't fully describe clearly, related content of design also can't completely decided. Therefore, it's a good way to deal with this kind of uncertainty knowledge through probability theory and fuzzy logic. Decoupling method based on satisfaction, by defining a minimum value satisfaction for function requirement, under a certain approximation or assumed conditions, enlarging or decreasing the functional requirements scope to get a decoupling design [19].

4.2.2 The coupling inside customization module

Similar to the coupling inside platform module, the coupling inside customization module is also divided into weak coupling and strong coupling. Individual parameters aim at product family members, which is equivalent to the general single product. But their corresponding design parameters can not affect product platform when satisfy the product individuation demands, since the platform structure has been fixed. The decoupling method of weak coupling is the same as " (1) The coupling inside platform module". But strong coupling is different, the design goal and constraint as well as the design capacity have been clear, structured coupling design and analysis method could be taken. Through decoupling, refactoring, split and so on, we can plan the coupling modules to determine the realization sequence of each function.

For the strong coupling, according to the size of coupling module, we decouple it in different ways. If there were only two FRs-DPs coupling designs, we split the parameters and analyze the dependencies and transitive relations between them to identify the operating parameters and controlled parameters. Operating parameters are controllable parameters, which affect the controlled parameters more than depend on them, so the iterative sequence is from the controllable parameters to the controlled parameters. As the lower-right module of Fig. 2, there are 2 FRs-DPs, 2 association parameters DP_{14} and DP_{15}. Assuming they are strong coupling. According to correlation dependence of design parameter and transfer analysis, we identify the controllable parameters DP_{14} and controlled parameters DP_{15}. Therefore, we should implement the corresponding functional requirements of DP_{14}, and then implement the corresponding functional requirements of DP_{15}.

When there are coupling designs with many FRs - DPs, we can use two-way comparison and intelligent optimization methods such as immune optimization method to solve the problem [16]. The judgment matrix is constructed by judgment criterion on each FR and DP, to get quantitative judgment about DPs' contributes to FRs and FRs' dependence on DPs. Then we comprehensively consider the quantitative results of FRs-DPs coupling degree to get the possible sorting vectors. In design parameters of all coupling modules, the first controllable parameter, second controllable parameter, ⋯, and controlled parameters can be identified, thus the best order of all coupling functions is determined.

4.2.3 The coupling association of design parameters between modules

The coupling association of design parameters between modules is due to the association elements not belonging to the modules in coupling correlation matrix of product family design, including the coupling association of design parameters between platform modules, the coupling association between platform module and customization platform module, and the coupling association of design parameters between customization platform modules. The internal coupling analysis of modules is to achieve the iterative sequence of the design, and the coupling analysis between modules is to evaluate correlation degree between the modules and to control and adjust design parameters.

(1) The coupling between platform modules

The coupling between platform modules is divided into one-way association and mutual association. The one-way association between modules means that one module influences but does not rely on another module, and the parameters can be adjusted by certain sequence to avoid the information feedback of the controlled parameters. It's also possible to avoid the association of design parameters by choosing the design parameters again.

The mutual association between platform modules means that two modules are associated with each other. In order to investigate the processing method of coupling association of design parameters between platform modules, we take the correlation description and analysis of two association modules as the example to illustrate (see Fig. 3 and Fig. 4). The design parameters DP_1-DP_4 and DP_5-DP_6 are considered as the inputs of modules 1 and 2, while the $\mathbf{FR}_1$ and $\mathbf{FR}_2$ as corresponding output of the two modules; the arrows in Fig. 4 represent information flows, which are used to describe the communication between modules 1 and 2; C_1 and C_2 are control factors, which respectively represents the related design constraint, (specification and criteria, etc, C_1 and C_2 respectively restricts the range of solutions for modules 1 and 2; M_1 and M_2 are mechanisms, which are the principles to achieve the FRs. As shown in Fig. 3, there are 2 association elements F and G outside the modules, specifically, the module 1 influences the DP_5 of module 2 through the design parameters DP_2, and the module 2 influences the DP_3 of module 1 through the design parameters DP_6. The change of module 1 will cause the change of module 2, similarly, the change of module 2 will also affect module 1. The relationship between the two modules is not close, because one of the goals of the coupling module clustering is to require the coupling degree of the modules as low as possible. At this point, according to the test design of coupling relation parameters, analyzing the impact of the two related parameters on the modules, judging the degree of mutual dependence between the modules, and determining the sequence of the modules.

DP	1	2	3	4	5	6	7	8
1	1							
2	1	1	1		←	Module 1		
3		1	1	1		①	←	*G*
4			1	1				
5		①			1			
6		↑			1	1	1	
7		*F*			1	1	1	1
8		Module 2 →					1	1

Fig. 3. Coupling relationship between platform modules for product family.

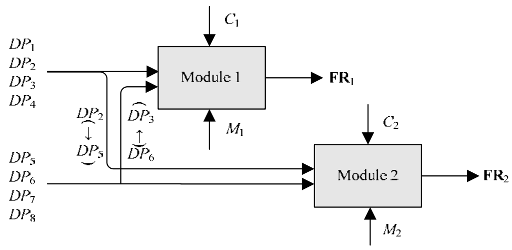

Fig. 4. Schematic diagram of coupling relation between platform modules.

(2) The coupling between platform module and customization module

When there exist association parameters between platform module and customization module in the coupling correlation matrix, there is coupling relation between them, as shown in

Fig. 5. Inspired by the match method of controlled variables and controllable variables in decoupling control system, it's possible to minimize the correlation between modules through selecting the reasonable match of the controllable parameters and controlled parameters of association parameters, which is also an effective method to weaken the coupling relation. As shown in Fig. 2, for the association element *C*, the controllable parameters is DP_8, the controlled parameter is DP_{13}. Through the reasonable match of DP_8 and DP_{13}, it can reduce the coupling relation between the modules containing the two parameters. Sometimes, the controllable parameters or controlled parameters have certain associations with other parameters or certain restraint mechanism leads to the inability to find direct parameter matching. At this time, it's also possible to achieve a better match by the appropriate combination of controllable parameters or controlled parameters with their correlative parameters. For the association element *D* in Fig. 2, the controllable parameter DP_6 affects the controlled parameter DP_{14}, which is coupled with DP_{15}. So it's possible to combine DP_{14} with DP_{15} and then reasonably match with DP_6.

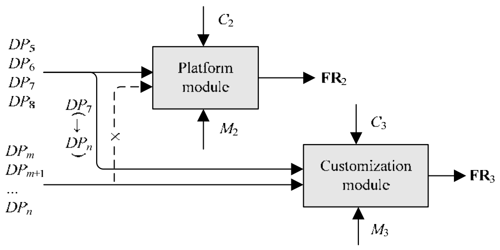

Fig. 5. Schematic diagram of association relation between platform module and customization module.

(3) The coupling between customization modules

Only after analyzing the two kinds of the above coupling relation, should it be possible to consider the coupling relation of design parameters between customization modules. Compared with the common platform module, it is in a subordinate position, because the customization parameters of product family only affect the difference of variant products. Each product variant has different customization parameters, of which some customization parameters only belong to certain product, while some customization parameters can vary in a larger range (which means they belong to a number of variant products).

The coupling relation of design parameters between customization modules can also be one-way correlation and mutual coupling, and the processing method can also refer to the method used in 1). While the difference is, for mutual coupling of customization modules, we should first consider their association with common platform parameters, and then analyze the modules' own interdependence, so as to determine the optimal sequence to achieve the function. As shown in Fig. 6, assuming there are 2 customization modules A and B, design parameters DP_A and DP_B respectively represents the input of the module A and module B, FR_A and FR_B are the outputs of the two module, DP_{c1} and DP_{c2} are the common platform parameters. At this time, there are three possibilities: (a) 2 modules are not affected by the platform parameters; (b) only 1 module is dependent on the platform parameters; (c) 2 modules are dependent on different platform parameters.

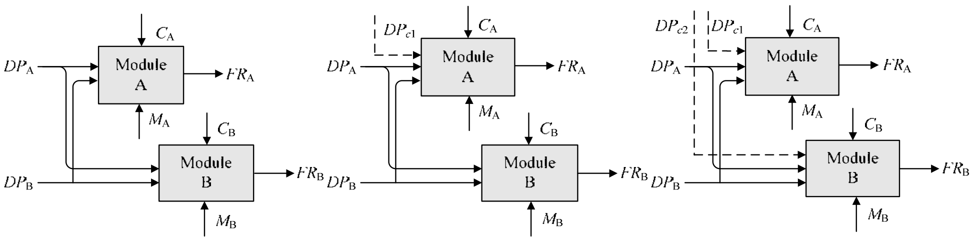

Fig. 6. (a) coupling relation without information input platform parameter; (b) Coupling relation with information input of platform parameters to one module; (c) Coupling relation with information input of platform parameters to 2 modules.

For the coupling relation without platform parameter input, as shown in Fig. 6(a), the 2 customization modules have interactions, but they are not subject to the impact of platform parameters, and the processing method is as the same as the processing method to the coupling relationship between 2 platform modules shown in Fig. 4.

As shown in Fig. 6(b), the two customization modules have interactions and one of them is dependent on platform parameters. Because the platform parameters prior to customization parameters are determined, we should achieve the match association of DP_{c1} and module A (or its internal customization parameters), and then analyze the coupling relationship between modules and focus on improving the adaptability of module B, to control the variation in the association parameter of module 2.

As shown in Fig. 6(c), the two customization modules are coupled and are affected by different platform parameters. We should find the reasonable match according to the platform parameters and the corresponding relationship of the modules (or its internal customization parameters), and then consider the reasonable match of the correlation parameters between the 2 modules, to control the variation in the association parameter.

5. Concluding remarks

To solve the coupling problem of product family design (or product platform planning), it can be achieved from the strategy level and operation level. In the view of platform strategy level, from the view of the customers' demands, it's easy to divide functional requirements of the product into basic functional requirements, expectable functional requirements and additional functional requirements. Axiomatic design theory is taken as a guide framework, the functional requirements are zigzagging mapping to design parameters, and the design matrix is created. The sensitivity among the design parameters and the sensitivity between design parameters and functional requirements are analyzed, and the difference degree of design parameters of product variants is calculated. Thus the platform parameters and customization parameters is reasonably identified. Based on the perspective of the platform operation level, the design matrix is converted into DSM, and DSM is reconfigured and clustered and grouped into modules with less dependent degree. The coupling correlation matrix of product family design is established, which can realize high cohesion degree in a single module and low coupling degree among all the modules. Then the interface among modules can be identified, and the association parameters are considered as controllable factors and experimental design techniques are utilized to analyze the influence of association parameters on the design objectives, so as to enhance the robustness of product family design and weaken the coupling of product family design. Finally, the coupling analysis is carried out from three aspects, which are the coupling inside the platform modules, the coupling inside the customization modules and the coupling association of design parameters between the modules, and then the corresponding design coupling process method is proposed.

Through the system research, this paper establishes the decoupling methodology of product family design. The methodology can overcome the lack in axiomatic design about disposing the coupling design, which better distributes the design resources, improves product design efficiency and the level of customization. Since the proposed method focus on the association of design parameters inside module and between modules, it is suitable for conceptual design and parameter design of modular series products, such as vehicle, universal crane, agricultural machinery, etc.

In the future, we will evaluate the coupling degree between modules by coupling association path and association influence degree, and validate the effectiveness of this work through the case study of product family design.

Acknowledgements

This work was supported by the National Natural Science Foundation of China under the Grant Nos. 71462007, 71171089 and 51165007.

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