Product Function-structure Modeling Based on Nodes Characteristic Matrix

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Abstract. Aimed at the problem of product modeling under Mass Customization, concepts of the characteristic matrix and matrix row were proposed. The function-structure model based on product network nodes was established by the combination and identification of characteristic matrix under the function-structure constraints and the function-structure mapping relationship of network nodes. Finally, the function-structure collaborative modeling of the translation mechanism was used as an example to illustrate that the method can simplify the repeatability of design under product rapidly customization.

1. Introduction

Nowadays, with the rapid development of computer technology especially the network technology, Customer requirement for the product is becoming more diverse and personalized. In order to meet the requirement of Customers and win the market share, the enterprise's production mode began to transform mass to small, personalization and diversification. Meanwhile, in order to improve the profits and reduce the cost, it needs meet personalized and diversified requirement at the efficiency of mass production, therefore, the Mass Customization (MC) [1] came into being.

Aim at MC, product structure model is a key technology to adapt this production mode at first, and some experts have made a number of researches. Gao et al [2], established product structure model adopting the modeling theory based on Generic Bill of Material (GBOM). The product modeling method based on the theory of the network graph [3] is more intuitive, but it is difficult to clearly express the father-son relationship between nodes. Therefore, product modeling based on complex networks has made considerable achievements. Erdos et al [4], established random network model (ER); Walts et al [5], established small-world network model (WS); Barrat et al [6], established scale-free network model; Liu et al [7], introduced the theory of complex networks into MC and established the structure model of product family. However, this model emphasizes the research on the topology structure of products, and ignored the functional and structural characteristic of nodes in the network of structure.

In this paper, concepts of the characteristic matrix and matrix row were proposed by the function-structure characteristic of product nodes; the function-structure model based on the theory of the node characteristic and complex networks was established [8]. Then, the method of structure identification based on matrix row was presented. The product instances meet the requirement of function and assembly rules between structures were configured.

2. Characteristic Matrix of Nodes

2.1 Establishment of Characteristic Matrix of Nodes

Mechanical products are made up of many parts, components and institutions through the assembly constraints. Different characteristic indexes such as geometric, functions, attributes, etc., are realized by different assembly relationships between components. Characteristic indexes of components were processed by parameterization, and formed into characteristic vector $cm=[x_1, x_2, \ldots, x_n]$, in which x_i is parameters of the corresponding characteristic index of components.

In order to simplify the characteristic matrix, components with the same characteristic index are used as a node to process, and reasonable cases in the component base are identified by characteristic indexes of some nodes. So the characteristic matrix of nodes can be defined as follow:

$$CM = \left[cm_1^T / c_1 \quad \ldots \quad cm_m^T / c_m \right]^T = \begin{pmatrix} x_{11} & \cdots & x_{1n} / c_1 \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} / c_m \end{pmatrix} \tag{1}$$

Where x_{ij} is a parameter of the characteristic index, c_i is the interface characteristic to connect corresponding elements of two neighbor nodes, including averagely size characteristics.

2.2 Rules of the Interface Characteristic

The characteristic matrix of nodes is not determined, it can be constituted by one or a series of characteristic indexes of components. Therefore, information transfer between adjacent nodes is decided by their interface characteristics. Because of the diversity of the characteristic of nodes and their interface characteristics, all the elements of interface characteristics within the nodes formed into the rule matrix *C*, it can be expressed as:

$$C = \begin{pmatrix} c_{11} & \cdots & c_{1l} \\ \vdots & \ddots & \vdots \\ c_{m1} & \cdots & c_{ml} \end{pmatrix}$$

Where, each column called the rule column. Parameter matched between nodes through rules established by their rule matrixes, where the rule constraint is expressed as "*If*…， *Then*…".

Therefore, the characteristic matrix of nodes has also this form: $CM_{m\times(n+l)} = \left[cm\right]_{n\times m}^T \cup \left[C\right]_{m\times l}$.

2.3 Example of the Characteristic Matrix

The characteristic matrix of the gear and shaft were established by their design parameters, main parameters of gears include modulus (*m*), reference diameter (*d*), dedendum (h_f), tooth width (*b*) and bore diameter (*D*), and shafts include main shaft diameters (d_i) and its length (l_i). As shown in Fig. 1, the interface characteristic of characteristic matrixes is ascertained by matching rules of the gear and shaft. For example, *b* and *D* are interface characteristic of gears, d_i and l_i are interface characteristic of shafts. The rule as "*If* $D=d_1$， $b=l_1$， *Then* $A \leftrightarrow B$ " where $A \leftrightarrow B$ can be defined as realization of gear and shaft.

Characteristic matrix of the gear

Interface Characteristic

Characteristic matrix of the shaft

$$\begin{matrix} d & m & h_f & s & b & D \end{matrix} \qquad \begin{matrix} d_1 & l_1 & d_2 & l_2 & d_3 \end{matrix}$$

$$\begin{bmatrix} 100 & 2.75 & 3.44 & 4.77 & 90 & 40 \\ 131 & 2.75 & 3.44 & 4.77 & 70 & 50 \\ 131 & 2.75 & 3.44 & 4.58 & 75 & 65 \\ 108 & 3 & 3.75 & 4.71 & 70 & 50 \\ 159 & 3 & 3.75 & 4.71 & 80 & 60 \end{bmatrix} \qquad \begin{bmatrix} 40 & 90 & 50 & 20 & 35 \\ 65 & 75 & 75 & 30 & 50 \\ 50 & 70 & 60 & 25 & 50 \\ 60 & 80 & 70 & 25 & 40 \end{bmatrix}$$

Fig.1 the characteristic matrix and interface of gears and shafts

3. Network Nodes Model

3.1 Product Network Nodes Model for MC

Face to MC, in order to meet the standard of product design and form into requirement index interaction structure which is clear function level, requirement indexes of customer are expressed formally. On this basis, the structure configuration module, which meets functional requirements, is formed by adjusting design parameters of functional requirements and constraint rules between the nodes. And combining with personalized requirement of customers and the standard of the product customization, realized customization of product which meets personalized requirement. Product network nodes model for MC is shown in Fig. 2.

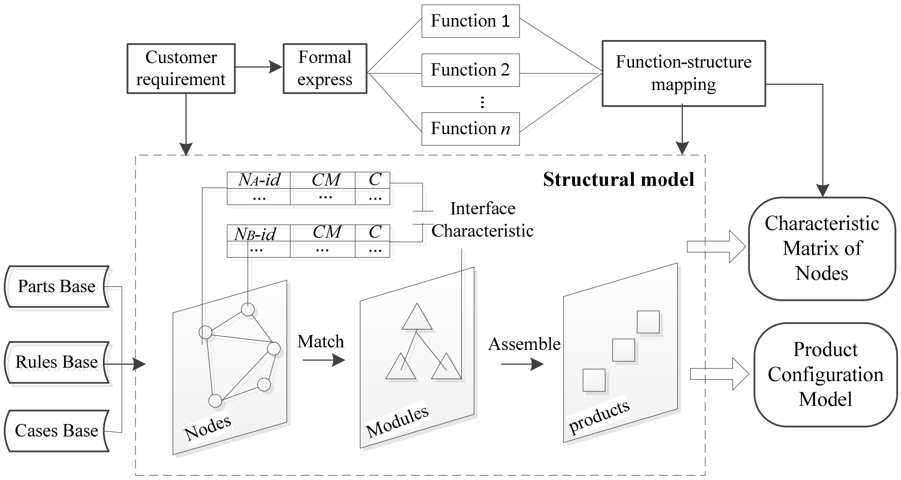

Fig. 2 product network nodes model for MC

3.2 Network Nodes Model Based on the Characteristic Matrix

The product network nodes model based on the characteristic matrix is based on the structure node defined by the characteristic index, which is established by the information transmission rules between nodes and their constraints. It can be expressed as follows:

NCR={*Nodes-id*, *Characteristic Matrix*, *Rules*} (2)

Where:

1) *Nodes-id* is node identification, include the product layer network nodes: *Product Nodes*=< N_i*-product* /*i*=1，2，3…>, the module layer : *Module Nodes*=< N_i*-module*/*i*=1，2，3…>, and the part layer: *Part Nodes* =< N_i*-part*/*i*=1，2,3…>;

2) *Characteristic Matrix* is a set of the node characteristic matrix, it can be expressed as *Characteristic Matrix*={CM_i /*i*=1，2，3…};

3) *Rules* is the transfer rules of the parameters of the characteristic matrix, it determines the information transmission rules between nodes and can be expressed as *R*={*Necessity Rules*, *Selectivity Rules*, *Coexistence Rules*, *Exclusiveness Rules*}.

3.2.1 Information Flow of Network Nodes

According to match rules, the information flow between the product layer, the module layer and the part layer node is determined. Fig. 3 is the diagram of information flow of the characteristic matrix.

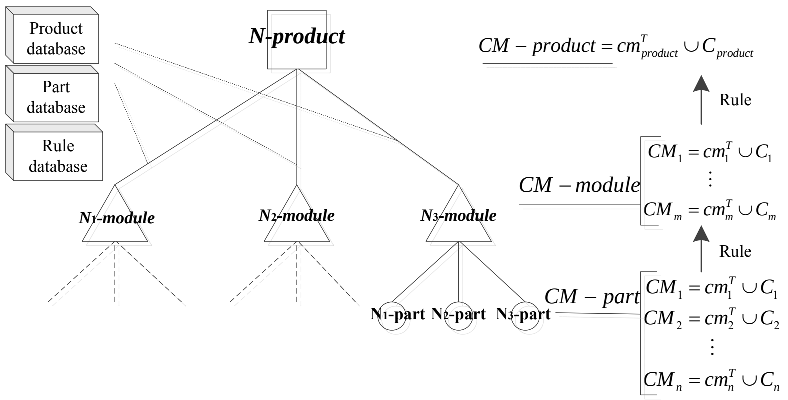

Fig. 3 the diagram of information flow of the characteristic matrix

3.2.2 Match Rule of Nodes

The interface characteristic rule determines the flow of the information flow of the node, and is a necessary process of the modular design. It includes structural rule, functional rule and constrained rule between the function and structure, etc. Structural rule is that the match of each node structure is realized by the fit of their physical dimension; Functional rule is that the match between functions is realized by the relationship such as the mutual dependence, exclusion, between function modules; The constraint rule based on the function-structure mapping is that the match between the function and structure is realized by the mapping relation between the function and structure. Based on these match rules, a variety of node characteristics matrix operations are realized, edit data is obtained, and product design is completed . These rules all include the necessity rule, selective rules, coexistence rules, and exclusiveness rules, they are shown in Table 1.

Table 1 match rule of nodes

Rule Type	Rule Definition	Reasoning Process	Range
Necessity Rules = <NR_i/i=1,2,3…>	If characteristic matrix $A_{m\times n}$ is called out, $B_{l\times k}$ must be called out.	*If* $A\in N$, *Then* $B\in N$ (*N* is the set of selected nodes)	Between characteristic matrixes
Selectivity Rules =<SR_i/i=1,2,3⋯>	If a_i in $A_{m\times n}$ is selected, any parameter in $B_{l\times k}$ can be selected.	*If* $a_i\in N$，*Then* b_j *or* $b_k \in N$	Between characteristic matrixes
Coexistence Rules =<CR_i/i=1,2,3⋯>	If a_i and b_i in characteristic matrix is selected, a_j and b_j can be selected.	$\{(a_i, b_i)\in N\}\cap\{(a_j, b_j)\in N\}\neq\emptyset$	Inside characteristic matrixes
Exclusiveness Rules =<ER_i/i=1,2,3⋯>	If a_i and b_i in characteristic matrix is selected, a_j and b_j cannot be selected.	$\{(a_i, b_i)\in N\}\cap\{(a_j, b_j)\in N\}=\emptyset$	Inside characteristic matrixes

4.Function-structure Mapping of Product Network Nodes

4.1 Structure Identification Based on Matrix Rows

Aim at two adjacent node characteristics matrix $A_{m\times n}$ and $B_{l\times k}$, according to functional requirement index of the customer and match rule of nodes, any row in $B_{l\times k}$ is traversed by each row parameter in $A_{m\times n}$. Raw vector a_i in $A_{m\times n}$ and b_j in $B_{l\times k}$ are matched by rules, so（a_i，b_j）is defined as a set of matrix row. Node characteristics matrix $A_{m\times n}$ and $B_{l\times k}$ can form $m\times n$ sets of matrix rows, and the initial match between components is realized.

A number of matrix rows are formed by $A_{m\times n}$ and $B_{l\times k}$, this is only the initial match between the components, the actual may not be reasonable, which requires matrix rows to be identified by requirement indexes. Structure identification based on matrix rows is shown as Fig. 4

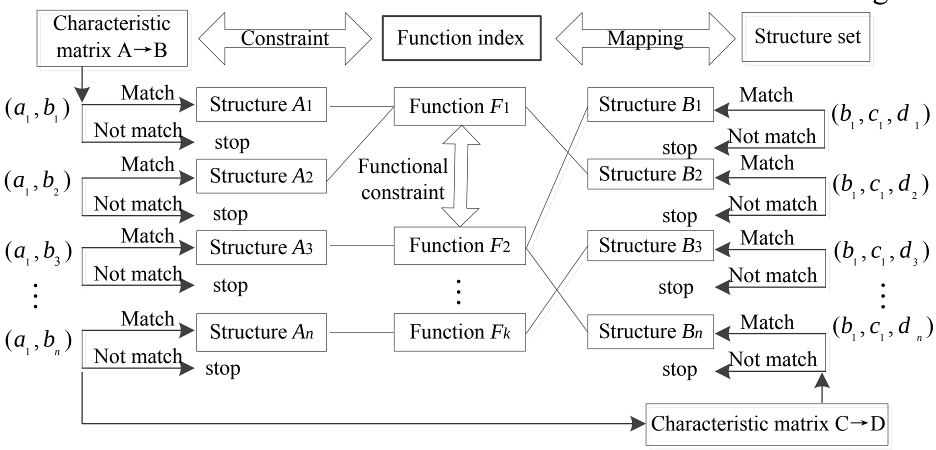

Fig. 4 Structure identification based on node characteristic matrix

According to Fig.4, its basic steps are as follow:

Step1. Aim at (a_i, b_j) under the constraint of rule matrix, if it can meet structural match rule, it will be saved and the corresponding structure S_{ij} and function F_{ij} will be defined, or abandoned directly.

Step2. In the same way, the structure S_{ij} corresponding to (b_i, c_p) will be obtained, and a new structure (a_i, b_j, c_p) is formed under structural constraints.

Step3. The structure (a_i ,b_j), (c_i ,d_j) corresponding to function F^1_{ij} and (a_i ,c_j) corresponding to F^2_{ij} are realized, so a new structure（a_i ,b_j ,c_j）is formed under functional constraints.

Step4. Repeat step 2 and 3, until the match of all nodes to meet structural and functional constraint.

Step5. Finally, product nodes meet requirements is obtained, expressed as $P=(a_i, b_j, c_k, d_l…)$.

4.2 Function-structure Mapping of Network Nodes

The network nodes model of product directly reflects the topology of the product, and the structure identification of the node characteristic matrix can form different organizations and products, but it is difficult to realize the series, diversification and meet personalized requirements of the customer. In order to facilitate the data's reading, avoid the interference between the information parameters, and improve the mapping efficiency from product function parameters to structure parameters, a mapping model from functional requirements matrix to design parameters matrix is established. The function-structure mapping process of product network nodes is the instantiated process of the function requirement index. It can be expressed as follow:

$$DP = D \cdot FR = \begin{pmatrix} d_{11} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & d_{mm} \end{pmatrix} \cdot \begin{pmatrix} fr_{11} & \cdots & fr_{1n} \\ \vdots & \ddots & \vdots \\ fr_{m1} & \cdots & fr_{mn} \end{pmatrix} \quad (3)$$

Where *DP* is the design parameters matrix $DP = \left[dp_1 \quad dp_2 \quad \cdots \quad dp_m \right]^T$, whose dp_i is the row vector of design parameters for component *i*; *D* is the design matrix, which is a diagonal matrix, in order to avoid the interference between functional requirement indexes and design parameters; *FR* is the functional requirements matrix $FR = \left[fr_1 \quad fr_2 \quad \cdots \quad fr_m \right]^T$, whose fr_i is the row vector of function characteristic index *i*. The customer's requirement for products can be one or more functions, so requirement coefficient matrix *S* is introduced. Because the functional requirements are mutually independent, *S* can be expressed as follow:

$$S = \begin{pmatrix} s_{11} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & s_{mm} \end{pmatrix}, \text{ where, } s_{ij} = \begin{cases} 0 & when\ i \neq j \\ 0 & when\ i=j,\ customers\ didn't\ select\ this\ function \\ 1 & when\ i=j,\ customers\ selected\ this\ function \end{cases}$$

Therefore, mapping relationship between functional requirements and structural parameters can also be expressed as: $DP = D \cdot S \cdot FR$

5. Example

In this paper, a method of product function-structure modeling for MC is illustrated with the example of designing a translation mechanism. The modeling process of the translation mechanism is shown in Fig. 5, expressed as follow:

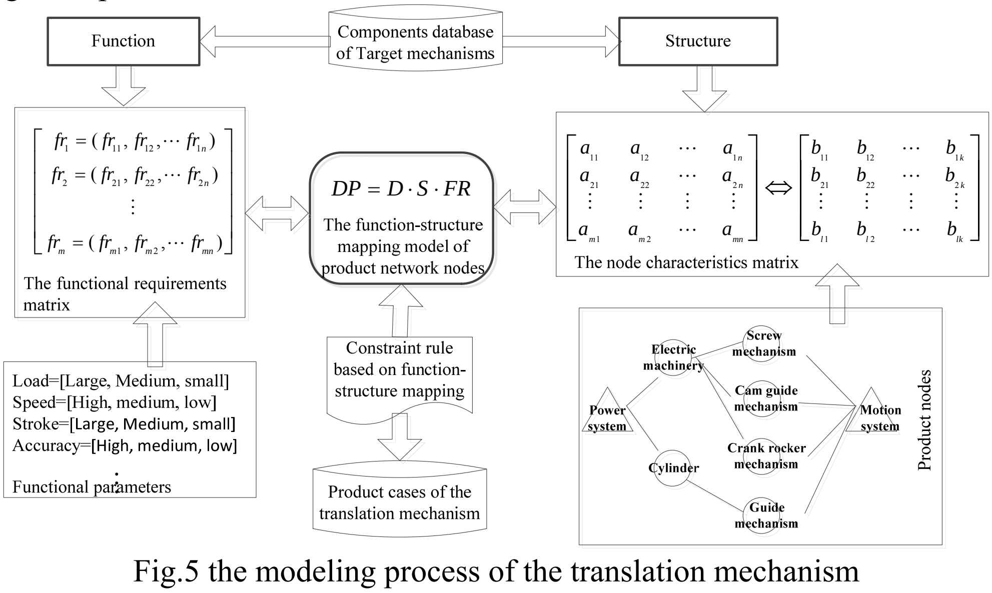

Fig.5 the modeling process of the translation mechanism

1) According to customer requirements and functional rules, related functions are selected, and the functional requirements matrix is defined;

2) According to functional requirement indexes and design parameters of components of the translation mechanism, the node characteristic matrix of the corresponding structure is established.

3) According to match rules of nodes, matrix rows with reasonable structure are constructed.

4) According to constraint rules of the function-structure map, design parameters of the corresponding mechanism are generated by further identification of matrix rows based on selected and related functions.

5) The structure-function modeling of products is realized, and a series of similar product cases are generated.

6) The configuration of requirement product is realized by design parameters of the mechanism, the customer's individual requirements and the enterprise product case base.

6. Summary

Aim at MC, the structure-function model of a network node power based on the node characteristic matrix of the product was established, and realized the mapping from customer's functional requirements to product design parameters. According to constraint rules of mapping relationship, the product structure was further constrained by the function and structure parameters, and the collaborative design of the customer and designer is realized. The function-structure mapping applied to product design, could reduce the conflict between the design information, improve the product design efficiency, and have certain reference value to the research on product modeling method.

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References

[1] G. N. Qi, X. J. Gu, J. R. Tan, et al. Technologies and applications of mass customization. Beijing: China Machine Press, 2003(in Chinese)

[2] J.Y. Gao, X. N. Chu , J. Q. Yan. Configuration design based on generic bill of materials. Computer Integrated Manufacturing Systems, 2007, 13(3): 417-424(in Chinese)

[3] L. L. Meng, C. G. Lu, M. Zhang, et al. Study on implementing way of product BOM with XML. Journal of Engineering Graphics, 2007, 28(3):163-168(in Chinese)

[4] P. Erdos, A. Renyi. On the evolution of random graphs. Bulletin of the International Statistical Institute, 1960, 38(4): 343-347.

[5] D. J. Watts, S. H. Strogatz. Collective dynamics of “small-world” networks. Nature, 393(1998): 440-442.

[6] A. Barrat, M. Barthelemy, A. Vespignani. Dynamic processes on complex network. Cambridge: Cambridge University Press, 2008: 55-77.

[7] F.Y. Liu. Research on component analysis and configuration technologies of mechanical product. Zhejiang University, 2006(in Chinese)

[8] Q. Xie, J. R. Tan, Y.X. Feng. Configuration Design Oriented Product Function-Structure Modeling. Journal of Computer-Aided Design and Computer Graphics, 2006, 18(4): 574-579(in Chinese)