Construction and Application of Product Fast Conceptual Design Knowledge Base Based on Configuration Flow Graph

Zhen-chong MO, Lin GONG*, Jin-yi WANG and Jun GAO
School of Mechanical Engineering, Beijing Institute of Technology, China

*Corresponding author

Keywords: Conceptual design, Design knowledge, Configuration flow graph.

Abstract. Complex and diverse product information and rapidly-iterated market competition context are common in the current product design areas. The rapid concept design of products is becoming a major challenge for product designers and enterprise R&D departments. Utilizing the design knowledge of 100 common products selected in the market, this study divides and realizes structured storage by function in the form of CFG matrix by introducing standard functions, components and flow lexicon. For application of matrix library, this paper proposes a template CFG search method based on similarity calculation to assist designers in implementing rapid conceptual design. Bicycle is exampled to verify the practicality of the constructed matrix library and the effectiveness of the proposed method.

Introduction

As a result of the complex diversification of customer demand and existing products, together with the speedy and efficient iteration of products and the global competitive market environment, how to quickly and accurately improve the existing products on the market is becoming a major challenge for product designers.

Rapid product design includes configuration design and variant design. Yang Xianhai et al.[1] studied the common product platform composition and proposed that derivative products are produced by selecting and replacing components in the product framework structure. Mourtzis D et al.[2] established a configuration model based on the "if-then" rule, and used the forward reasoning method to guide customers to obtain effective configuration schemes. Qiu Lemiao et al.[3] researched the impact of dynamic changes in customer demand on product variant design, and established a design structure matrix to represent changes in product structure. Paoletti[4] suggested an example-based rapid product variant method, and discussed the importance and method of establishing an example platform.

The product concept term set is the basis of the structured description of product concept, which has an extremely important role and can be divided into three parts: functional term set, flow term set and component term set. Initially, Collins et al. developed a terminology set of 105 mechanical functions[5] for storing and retrieving helicopter fault information. Pahl and Beitz then built a highly abstract set of functional terms, including five functional terms and three flow terms[6]. On this basis, Little and Wood built a set of functional terms[7], including 8 functional categories and 3 flow categories, which laid the foundation for function and flow classification. Thanks to the research and expansion of Robert and his team, a more complete product concept model terminology set Function Basis (FB)[8] has been formed. For the component terminology mainly
covers the field of electromechanical products, Kurtoglu built the Component Basis for electromechanical products, which contains 92 terms and each represents a sub-category covering all common functions of electromechanical products[9].

In terms of structural representation of product concept, researches can be divided into two categories: the one centering on product function and the one on product components. Paul and Beitz proposed the Function Structure (FS) concept[6], and Tomiyama and Umeda proposed a new structural representation method Function-Behavior-State (FBS)[10]. As the term set of Function Basis[11] and Component Basis[9] continuously improved, Kurtoglu proposed the Configuration Flow Graph (CFG), a product concept representation method [12].

After synthesizing multiple classical functions, components, and flow standard language libraries, and then decomposing functional modules for 100 products on the market, this study first proposes the product function modules-component-function tree diagrams. Secondly, by formulating the coding rules of structured CFG basing on knowledge of CFG, the study proposes the product function module CFG matrix and forms a matrix library. To facilitate designers on quicker combination and linkage of product design knowledge, the study then proposes a template CFG search technology to help better achieve product concept design. Finally, the effectiveness of the constructed database and the feasibility of the proposed technology are verified.

Research Framework

The input to this study is the design knowledge of 100 products common in the market designers obtained through pre-analysis. In order to accurately and comprehensively express these design knowledge, a product function module CFG matrix library need to be formed. In order for a better application of the established matrix library, this study, using the similarity calculation method, searches the matrix library for template CFG with higher similarity to CFG of each target modules of target product, thereby assisting the designer to complete the product rapid concept design. The research framework is shown in Figure 1.

Construction of Product Function Module CFG Matrix Library

This chapter introduces the process of building the CFG matrix library of product function modules. Its function is to modularize the product design knowledge by function and to express it in the form of CFG. Additionally, for the purpose of effectively using these design knowledge, it is structurally stored for easy analysis at the data level.
The CFG decomposition process of product function modules requires to introduce standardized functions, components and flow vocabularies so as to unify all kinds of complex products on the market. In this study, the above RFB term set is directly used as the standard function lexicon and flow lexicon, and the CB constructed by Kurtoglu is used as the standard component lexicon, with which to be the basis for the CFG decomposition characterization of the product function module. A part of the standard lexicon used in this paper are shown in Table 1. There are 191 function standard vocabularies, 106 component standard vocabularies, and 50 flow vocabularies.

<table>
<thead>
<tr>
<th>No.</th>
<th>Functions</th>
<th>No.</th>
<th>Components</th>
<th>No.</th>
<th>Flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>187</td>
<td>Fix</td>
<td>102</td>
<td>Steering_gear</td>
<td>46</td>
<td>Mass flow</td>
</tr>
<tr>
<td>188</td>
<td>Position</td>
<td>103</td>
<td>Rotational</td>
<td>47</td>
<td>Intensity</td>
</tr>
<tr>
<td>189</td>
<td>Align</td>
<td>104</td>
<td>Signal_generator</td>
<td>48</td>
<td>Decay rate</td>
</tr>
<tr>
<td>190</td>
<td>Locate</td>
<td>105</td>
<td>Corona</td>
<td>49</td>
<td>Temperature</td>
</tr>
<tr>
<td>191</td>
<td>Orient</td>
<td>106</td>
<td>Signal_receiver</td>
<td>50</td>
<td>Heat flow</td>
</tr>
</tbody>
</table>

As the standard lexicons continuously improved, Kurtoglu projected the Configuration Flow Graph (CFG), a product concept representation based on the product component structure. This paper uses the configuration flow diagram (CFG) to represent the concept of function modules in a product.

In this study, the product function module CFG structured data decomposition process has three steps. First, based on the introduced standard function and component lexicon, the target product is disassembled into function modules-component-function tree diagram. Secondly, according to the analysis and judgment of designers, the flow information is analyzed on the basis of the tree diagram, and the product function module CFG is formed. Finally, CFG decomposed by the above process is transformed into a product function module CFG matrix.

**Construction of Function Module—Component—Function Tree Diagram.** This section introduces the product function module-component-function tree diagram construction. Its purpose is to divide the product design knowledge according to different function modules, and introduce standard function and component lexicon to fully express the existing design knowledge.

The product function module-component-function tree diagram is formed by the designer based on the standard function lexicon and component lexicon and the design experience. It aims at the main function module analysis, component disassembling and the corresponding function analysis of the product. In the process of tree diagram decomposition, two rules are defined as follows:

**Rule 1:** The serial number of the target product function module is sorted according to its level of importance. The most important function module (i.e., the main function module) has a serial number of 1, and so on;

**Rule 2:** In a tree diagram, a standard function word can correspond to one or more components, but each component can only correspond to at most one standard function word.
The function module—component—function tree diagram is shown in Figure 2:

**Construction of Product Function Module CFG Matrix.** This section introduces the construction of CFG matrix of product function modules. Thanks to the concept of stream introduced through CFG, the design knowledge is expressed more accurately and comprehensively, and the structured storage is realized, which paves the way for data level analysis.

In the above research, after determining the product function module components, each component is used as a node of the configuration flow graph, in which the corresponding component lexicon is used for its meaning. At the same time, the connection between each two components is directed. The arrow flow indicates that the corresponding stream lexicon in the stream lexicon is used as the arrow stream meaning, and finally the configuration flow graph of a product function module is formed. The schematic diagram of the product function module CFG is shown in Figure 3:

**Secondly, this study converts the above product function module CFG into computable structured data through certain coding rules and methods, that is, forms the product function module CFG matrix.** The construction process is as follows:

**Step 1:** Construct an improved adjacency matrix $A$, which records components of the function module CFG. The function module CFG component nodes are numbered 1~N, and the first N row and the first N column of the improved adjacency matrix $A$ are respectively N component nodes of the function module CFG, and the N+1 row and the N+1 column represent the input and the output of the external environment on the function module. The matrix $a_{ij}$ is the standard flow number of the flow from node $i$ row to the node $j$ row, and if there is no flow between the two nodes, $a_{ij}$ is set to 0.

**Step 2:** Second, build the additional matrix $B$. The additional matrix $B$ is actually added to improve the node meaning of the adjacency matrix $A$. The additional matrix size is $2 \times (N+1)$, the
first row is set as component vector C, and the first N elements respectively represent the standard component word number of the corresponding node, that is, \( c_j \) represents the component meaning of the node j. In order to form a complete matrix with columns in the improved adjacency matrix, add the element 0 to the N+1. Vector F is in the second row of additional matrix. Similar to the component vector construction method, replace the element with the standard function word number of the corresponding node, that is, \( c_j \) represents the functional meaning of the node j. The third row of additional matrix is the function module serial number vector Num. Add a row with \((N+1)\) elements below each CFG matrix of the function module, in which the value of each element is the same, and mark them with product function module serial number corresponding to the matrix.

Next, the improved adjacency matrix A and the additional matrix B are spliced together to obtain a complete structured function module CFG matrix. The final structured matrix is shown in Figure 4:

![Figure 4. The schematic diagram of the product function module CFG matrix.](image)

**Template CFG Search for Fast Concept Design**

This chapter introduces the template CFG search method in the CFG matrix library. It aims to realize the analysis and application of the established design knowledge base, and, based on the search results, assist the designer for rapid concept design.

Facing certain product rapid concept design problems, designers can first form the target product CFG matrix, then search for the similar template CFG in the constructed CFG matrix database, and finally combine the template CFG of each function module for viable solutions to the problem.

Template CFG search based on similarity calculation: The similarity calculation is performed on the CFG matrix of the target product function module and the CFG matrix in the database, and the existing data with high similarity to the CFG to be improved is selected. In the similarity calculation, the similarity of the function vector is given the maximum weight, while of the component vector similarity weight the smaller weight, and of the adjacency matrix of the stream information the minimum weight. Therefore, the similarity calculation formula is designed as follows:

\[
D = \omega_f \cdot Jaccard(F_t \cdot F_m) + \omega_c \cdot Jaccard(C_t \cdot C_m) + \omega_a \cdot Jaccard(A_t \cdot A_m)
\]

Among them, \( F_t \) represents the function vector of the target CFG, and \( F_m \) represents the
function vector of the template CFG. The Jaccard similarity coefficient formula is:

\[
\text{Jaccard}(A \cdot B) = \frac{|A \cap B|}{|A \cup B|}
\]  

(2)

In this study, make \( \omega_f = 0.5, \omega_c = 0.3, \omega_a = 0.2 \).

**Case Study**

The researchers took the common bicycles on the market as an example, and decomposed them into CFG matrices bounded by function modules. Rapid concept design was realized under the guidance of the fourth part of this research.

First, researchers made a function module-component-function tree diagram of the target product (bicycle) in accordance with the content described in Section 3.1 and the standard function lexicon and component lexicon, as shown in Figure 5. Secondly, researchers formed the CFG function module according to the content of 3.2. Then, the CFG was converted into CFG matrix according to the content of 3.3. Figure 6 is an analysis example of the adjustment module. The final CFG matrix of the target product (bicycle) is shown as Figure 7:

![Figure 5. The function modules-component-function tree diagram of bicycle.](image)

![Figure 6. An analysis example of the adjustment module.](image)
Through the similarity calculation, the template CFG of each function module is searched, and the result is as follows:

Table 2. Template CFG of bicycle.

<table>
<thead>
<tr>
<th>Bicycle Function Module</th>
<th>Template CFG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive</td>
<td>Pedal machine-1 Electric bike-1 Motorcycle-1 Wheelchair-2 Roller skates-1</td>
</tr>
<tr>
<td>Guide</td>
<td>Electric bike-2 Motorcycle-2 Automobile-3 Wheelchair-3 Skateboard-3 Balance car-3</td>
</tr>
<tr>
<td>Brake</td>
<td>Electric bike-3 Motorcycle-3 Wheelchair-3</td>
</tr>
<tr>
<td>Support</td>
<td>Wheelchair-1 Motorcycle-4 Electric bike-4 Lifting chair-1 Fitness machine-2</td>
</tr>
<tr>
<td>Adjustment</td>
<td>Fitness machine-3 Jack-2 Lifting chair-2</td>
</tr>
</tbody>
</table>

Based on this result, the researchers combined the template CFG to find a feasible solution to the design problem, and formed a rapid conceptual design as shown in Figure 8.

Conclusion

The research aims to effectively and comprehensively integrate existing product design knowledge, and, by knowledge analysis and application from the data level, facilitate the rapid concept design process of the product. Utilizing the design knowledge of 100 common products selected in the market, this study divides and realizes structured storage by function in the form of CFG matrix by introducing standard functions, components and flow lexicon. For application of matrix library, this paper proposes a template CFG search method based on similarity calculation to assist designers in implementing rapid conceptual design. Bicycle is exampled to verify the practicality of the constructed matrix library and the effectiveness of the proposed method.

However, the designed products are still insufficient in the respects of technical iteration and innovation. In the future work, more attention should be paid to data performance capabilities and application methods of the matrix library in terms of technical feasibility and evolution trend.
Acknowledgement

The research was supported by a National Key Research and Development Project (No. 2018YFB1700802) and a National Ministry Basic Research Project (No. JCKY2016203A017) and a National Natural Science Foundation of China (No. 51405018).

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