Title:
Design of Multi-functional Product by Searching Shareable Functional Components

Authors:
Jinpu Zhang, jinpu_zhang@163.com, Hebei University of Technology
Qingjin Peng, Qingjin.Peng@umanitoba.ca, University of Manitoba
Guozhong Cao, caoguozhong@hebut.edu.cn, Hebei University of Technology
Runhua Tan, rhtanhebut@163.com, Hebei University of Technology
Huangao Zhang, zhgzwy@hebut.edu.cn, Hebei University of Technology
Wei Liu, lwofhebut@126.com, Hebei University of Technology

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Introduction:

With the rapid development of diverse products in the market, many products are only used in a specific application with limited functions, resulting in a waste of resources of materials and space. A multi-functional product can provide different functions for various applications using less resources. Some of these products perform multi-functions through the structural reconfiguration [8]. A systematic approach is needed to design such product. Although a number of methods have been developed for product design, there is a lack of the effective method to search sharable functions from different products to form a multi-functional product.

There are two types of components in a reconfigurable or multi-functional product. One is the single functional component, the other is the sharable functional component [1]. The more sharable functional components are, the less material and space the product will use compared to the single-functional product. Therefore, it is significant to increase the number of sharable functional components in a product. Lewis et al [4] used a functional similarity matrix of two products to analyze their correlations of components through a component-component matrix. However, there is a lack of details in the method of the similarity search for functional elements and formation of related elements. This paper proposes a method to search function similarity of components in different products in order to combine these components to form a multi-functional product. A similarity analysis of functional elements is first conducted based on products' flows and function descriptions represented by a functional element similarity matrix (FESM). A component-component similarity matrix (CCSM) is then built based on the functional element-component correlation matrix (FECCM). After then, an optimal search matches components from CCSM according to the component correlation. A multi-functional product is finally designed using the proposed method based on the similarity analysis of the electric shaver and cleaning brush. The design solution verified effectiveness of the proposed method.

Main Idea:

Similarity analysis of functional elements

Based on selected products to be combined for their common functions, functional structures of the products can be defined. Their functional elements are arranged in an action order of control-energy-transmission-execution to establish a similarity matrix [5]. An example of FESM for two products is shown in Fig. 1.

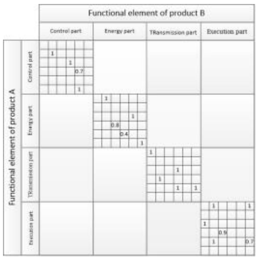


Fig. 1: Functional element-component correlation matrix.

Element x_{ij}^{FSM} in the matrix represents the degree of similarity between the *ith* functional element in product A and the *jth* functional element in product B. As shown in Eqn. (1). Where $\mathrm{x}_{\mathrm{ij}}^{\mathrm{f}}$ represents the degree of similarity of two functional elements, and $\mathrm{x}_{\mathrm{ij}}^{\mathrm{d}}$ represents the degree of similarity of two functional elements in the functional description.

$$\mathrm{x}_{ij}^{FSM} = \frac{1}{2}\left(\mathrm{x}_{\mathrm{ij}}^{\mathrm{f}} + \mathrm{x}_{\mathrm{ij}}^{\mathrm{d}}\right) \tag{1}$$

As complexity and uncertainty of objective things and fuzziness of human thinking, it is better to use ranking of fuzzy numbers to represent people's views on things than assigning a certain value. Flows of material, energy and signal in a product can be represented as $X = \{x_1, x_2, x_3\}$ [6]. These flows have different design weights for action elements of energy, control, transmission, and execution. Comparing importance of these flows of each elements, a triangular fuzzy number matrix can be obtained as $A = (a_{ij})_{3\times3}$, where $a_{ij} = [a_{ij}^L, a_{ij}^M, a_{ij}^U]$.

$$a_{ij}^L + a_{ji}^U = a_{ij}^M + a_{ji}^M = a_{ij}^U + a_{ji}^L = 1, \;\; a_{ii}^L = a_{ii}^M = a_{ii}^U = 0.5, \;\; a_{ij}^U \ge a_{ij}^M \ge a_{ij}^L, \;\; i, j \in N$$

Where, a_{ij}^L and a_{ij}^U refer to the lower and upper bounds of the importance, and a_{ij}^M refers to the most probable importance. Values of importances are defined in Tab. 1. Weights of these flows can be obtained using the FOWA operator [10] and represented as $\omega = (\omega_1, \omega_2, \omega_3)^T$.

Values	Definition
0.9	Extremely important
0.8	Strongly important
0.7	Obviously important
0.6	Slightly important
0.5	Equally important
0.4-0.1	Contrary to the above

Tab. 1: Importance scale values.

When flow k (k =1, 2, 3) of the *ith* functional element of product A is same as flow k of the *jth* functional element of product B, $S_{Aik} = S_{Bjk} = 1$, otherwise $S_{Aik} = S_{Bjk} = 0$. The similarity between the flow of the *ith* function element in product A and the flow of the *jth* function element in product B is defined in Eqn. (2), where, $f_{Aik} = \omega_{Ai} S_{Aik}$, $f_{Bjk} = \omega_{Bj} S_{Bjk}$, $k = 1, 2, 3$, $i, j \in N$.

$$\mathrm{x}_{ij}^{f} = Sim\left(F_{Ai}, F_{Bj}\right) = \frac{f_{Ai1} f_{Bj1} + f_{Ai2} f_{Bj2} + f_{Ai3} f_{Bj3}}{\sqrt{f_{Ai1}^2 + f_{Ai2}^2 + f_{Ai3}^2} \bullet \sqrt{f_{Bj1}^2 + f_{Bj2}^2 + f_{Bj3}^2}} \tag{2}$$

x_{ij}^{FSM} can be obtained from Eqn. (1) after $\mathrm{x}_{\mathrm{ij}}^{\mathrm{f}}$ and $\mathrm{x}_{\mathrm{ij}}^{\mathrm{d}}$ are decided using the synonym analysis software.

Identifying sharable functional components

FECCM is built based on relations of components and functions as shown in Fig. 2.

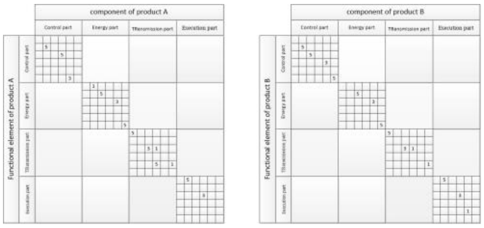


Fig. 2: Functional element-component correlation matrix (FECCM).

CCSM can then be formed as follows.

$$[CCSM]_{mn} = [FECCM]_{im}^{T} \times [FESM]_{ij} \times [FECCM]_{jn} \, (3)$$

The greater the value of element X in CCSM, the higher the functional similarity between the *ith* component in product A and the *jth* component in product B, and the possibility to be combined for a shared function in a multi-functional product. A bipartite graph is therefore constructed to search optimal matches of components with the functional similarity as shown in Fig. 3. Values are assigned for each element in X, which is the maximum value of the element in a line to connect to Y, and the value of Y is 0. For each element in X, the hungarian algorithm is used to find an augmented path in the equal subgraph. If the path cannot be found, the value of the element X is modified to expand the equal subgraph until an augmented path is found. When all the elements in X find their augmented paths, the optimal match is obtained [2].

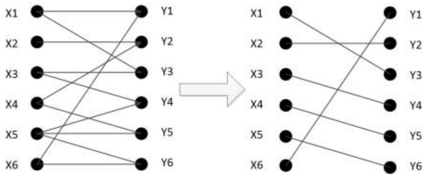


Fig. 3: Searching the optimal match.

CCSM as shown in Fig. 4. When the value of an element in the normalized CCSM is 1 or close to 1, the related two components are selected as shared functional components in the new multi-functional product. Modifications may be required for components to satisfy both functional requirements of products A and B. It is suggested to use TRIZ [3] or transformation principle and transformation facilitator [8] to guide the process. Components with less similarity should be considered as independent parts.

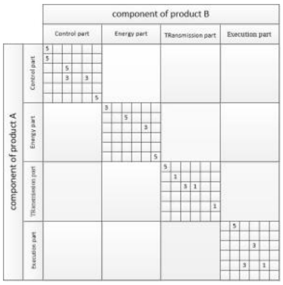


Fig. 4: Component-component similarity matrix.

Case study
An electric shaver and a cleaning brush are considered to be combined into a multi-functions product in this case study. The main function of an electric shaver [7] is to cut off the beard, while the electric cleaning brush [9] is to separate stains. Functional structures of the electric shaver and cleaning brush are shown in Fig. 5.

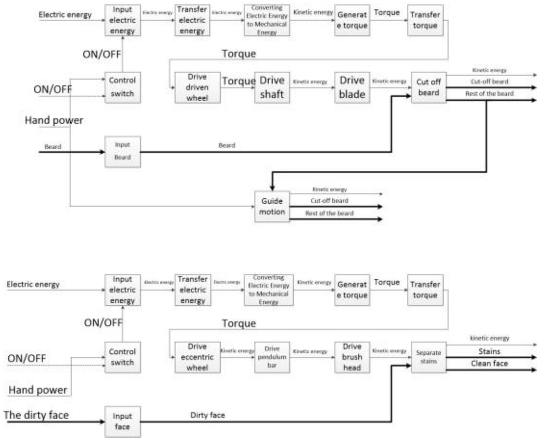
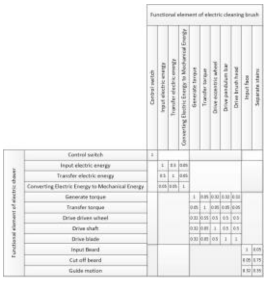


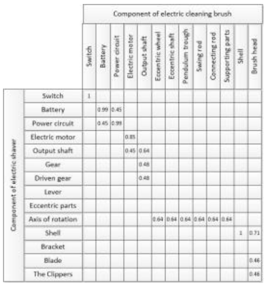
Fig. 5: Functional structures of the electric shaver and cleaning brush.

Using Eqn. (1), a FESM of the two products can be obtained as shown in Fig. 6.



		Functional element of electric cleaning brush										
		Control switch	Input electric energy	Transfer electric energy	Converting Electric Energy to Mechanical Energy	Generate torque	Transfer torque	Drive eccentric wheel	Drive pendulum bar	Drive brush head	Input face	Separate stains
Functional element of electric shaver	Control switch	1										
	Input electric energy		1	0.5	0.05							
	Transfer electric energy		0.5	1	0.05							
	Converting Electric Energy to Mechanical Energy		0.05	0.05	1							
	Generate torque					1	0.05	0.32	0.32	0.32		
	Transfer torque					0.05	1	0.05	0.05	0.05		
	Drive driven wheel					0.32	0.55	0.5	0.5	0.5		
	Drive shaft					0.32	0.85	1	0.5	0.5		
	Drive blade					0.32	0.85	0.5	1	1		
	Input Beard										1	0.05
	Cut off beard										0.05	0.75
	Guide motion										0.32	0.35

Fig. 6: FESM of the electric shaver and cleaning brush.



		Component of electric cleaning brush												
		Switch	Battery	Power circuit	Electric motor	Output shaft	Eccentric wheel	Eccentric shaft	Pendulum trough	Swing rod	Connecting rod	Supporting parts	Shell	Brush head
Component of electric shaver	Switch	1												
	Battery		0.99	0.45										
	Power circuit		0.45	0.99										
	Electric motor				0.85									
	Output shaft				0.45	0.64								
	Gear					0.48								
	Driven gear					0.48								
	Lever													
	Eccentric parts													
	Axis of rotation						0.64	0.64	0.64	0.64	0.64	0.64		
	Shell												1	0.71
	Bracket													
	Blade													0.46
	The Clippers													0.46

Fig. 7: Normalized and filtered CCSM of the two products.

Because the functional performance of these two products is at the same level, the similarity of these functional elements can be directly compared. Its CCSM is obtained using Eqn. (3), the CCSM is then normalized and filtered as shown in Fig. 7. After the optimal matching, a list of sharable functional components can be obtained as shown in Tab.2. The value in this table shows the degree of similarity.

When designing a multi-functional product, such components as switches and shells are used as shared functional components by making minor structural or parameter adjustments. Components with slightly lower correlations, such as the axis of rotation and eccentric shaft, may have some conflicts and problems if they are used as shared functional components. It is suggested to apply TRIZ or transformation principle and transformation facilitator to guide the design. Low-correlation components, such as blade and brush head, should be considered as separated parts.

The electric shaver	The electric cleaning brush	Value
Switch	Switch	1
Shell	Shell	1
Battery	Battery	0.99
Power circuit	Power circuit	0.99
Electric motor	Electric motor	0.85
Output shaft	Output shaft	0.64
Axis of rotation	Eccentric shaft	0.64
Blade	Brush head	0.46

Tab. 2: Sharable functional components.

Conclusions:

In this research, the functional similarity of components in different products is searched using product function descriptions. A CCSM is built by combining the FESM and functional element-component matrix. The graph theory is applied to search the optimal match of shareable functional components. According to values of components in the CCSM, sharing decisions can be made for design of a new multi-functional product.

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