Design for Multi-functional Product by Searching Shareable Functional Components

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Abstract. A product with multiple functions can save resources such as material and space compared to single function products. A multi-functional product can be designed through the structural transformation and reorganization of different products. It is a challenge for designers to combine different single-functional products into one to perform multi-functions. This paper proposes a method based on the similarity analysis of flow and function descriptions of different products to form a multi-functional product. A functional element similarity matrix (FESM) is formed first based on the existing products. A component-component similarity matrix (CCSM) is then obtained by combining the functional element-component correlation matrix (FECCM) with FESM. An optimal match of design similarity is searched according to values of CCSM to form the multi-functional product. A product is designed with combined functions of the electric razor and cleanser using the proposed method in a case study.

Keywords: Product Design, Multi-functional Product, Functional Element, Shared Components, Design Matrix
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1 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 such as 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 [15]. For example, an amphibious car combines the structure of automobile and small yacht to form a multi-functional vehicle. A systematic approach is needed to design such product.

Different methods have been proposed for the product design. Adaptive design aims to improve two levels of the adaptability [4, 5]. One is design adaptability for creating new designs or modifying existing designs according to changing needs, the other is product adaptability for the physical structure of products for changing needs. Product adaptability is usually achieved by modifying existing products, such as adding, deleting and replacing new components or modules. A kind of machines with functional adaptability by replacing system components or adjusting the connection mode of system components can be called the adaptive functional machine [18]. Reconfigurable design is mainly used to design reconfigurable manufacturing systems that are proposed for rapid changes in structure, hardware and software components, in order to quickly adapt sudden changes in the different production capacity and market demand [7]. Reconfigurable machines refer to the hardware system of reconfigurable manufacturing systems [1]. Transformation is a process of changing the physical form of a system in order to add new functions or enhance existing functionality [14]. Although many approaches have been proposed for product design such as above-mentioned methods, there is a lack of the effective way for design of the 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 [20]. Figure 1 shows two single-functional products. A, B and C represent components, and lines between them represent connections. Figure 2 shows two multi-functional products that perform the above two functions of products 1 and 2. The red area in Figure 2 represents the sharable functional components. Obviously, the number of sharable functional components in Figure 2 (a) is more than that in Figure 2 (b). The more sharable functional components a multi-functional product has, the less material and space the product will use. Therefore, designers can increase the number of sharable components in a product to enrich the product function and reduce the use of resources.

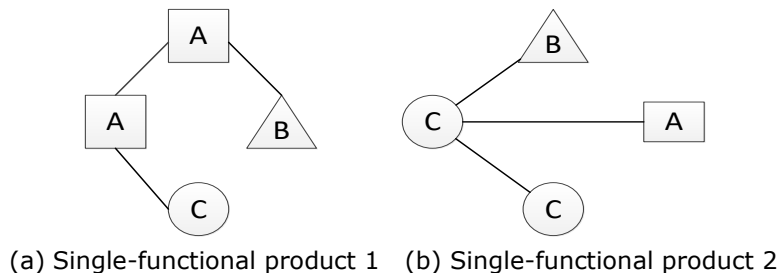(a) Single-functional product 1   (b) Single-functional product 2

Figure 1: Two single-functional products that perform different functions with components A, B and C.

(a) multi-functional product 1   (b) multi-functional Product 2
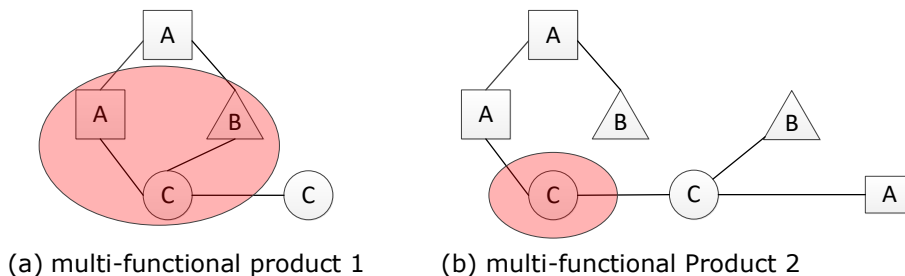
Figure 2: Two multi-functional products to perform functions of both products in Figure 1.

Lewis et al [8] and Tang et al [6] 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 the formation of related elements. This paper proposes a method to search the 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 flows and function descriptions of products 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 developed in a case study using the proposed method for the similarity analysis of the electric shaver and cleaning brush. The design solution shows effectiveness of the proposed method.

2   PROPOSED METHOD

2.1 Similarity Analysis of Functional Elements

Function is the conversion of material, energy and signal for a useful process [11]. As shown in Figure 3, a functional element is the minimum unit of the function, including function description, input flow and output flow. Functional elements are connected together by flows, called functional structures [11]. The purpose of components is to perform the function, that is to complete the flow conversion so that the similarity of functions performed by components is directly related to the substitutability of the components. Functional descriptions use the standard vocabulary [2].

Figure 3: Composition of functional element.

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 [10]. For example, Figure 4 shows the similarity matrix of functional elements for two products A and B.

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 Equation (1).

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

Where X_{ij}^{f} represents the degree of similarity of two functional elements, and X_{ij}^{d} represents the degree of similarity of two functional elements in the functional description. The similarity of functional elements considers the performance of functions such as the maximum force and minimum energy generated.

As the complexity and uncertainty of objective things and fuzziness of human thinking, a ranking of fuzzy numbers is used to represent people's views on things rather than assigning a certain value [17]. Flows of material, energy and signal in a product can be represented as $X = \{x_1, x_2, x_3\}$ [11]. These flows have different design weights for action elements of energy,

control, transmission, and execution. By comparing the importance of these flows for each element, a triangular fuzzy number matrix can be obtained as $A = (a_{ij})_{3 \times 3}$, where $a_{ij} = [a_{ij}^L, a_{ij}^M, a_{ij}^U]$.

$$a_{ij}^L + a_{ji}^U = a_{ij}^M + a_{ji}^M = a_{ij}^U + a_{ji}^L = 1, \ \ a_{ii}^L = a_{ii}^M = a_{ii}^U = 0.5, \ \ a_{ij}^U \geq a_{ij}^M \geq a_{ij}^L, \ \ i, j \in N \qquad (2)$$

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 Table 1 [9]. Weights of these flows can be obtained using the FOWA operator [17] represented as $\omega = (\omega_1, \omega_2, \omega_3)^T$.
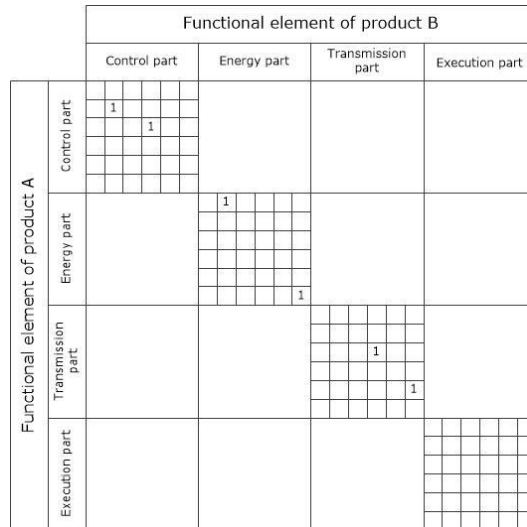
Figure 4: Functional element-component correlation matrix (FESM) for two products A and B.

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

Table 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 Equation (3), where, $f_{Aik} = \omega_{Ai} S_{Aik}$, $f_{Bjk} = \omega_{Bj} S_{Bjk}$, $k = 1, 2, 3$, $i, j \in N$.

$$x_{ij}^f = Sim\left(F_{Ai}, F_{Bj}\right) = \frac{f_{Ai1}f_{Bj1} + f_{Ai2}f_{Bj2} + f_{Ai3}f_{Bj3}}{\sqrt{f_{Ai1}^2 + f_{Ai2}^2 + f_{Ai3}^2} \bullet \sqrt{f_{Bj1}^2 + f_{Bj2}^2 + f_{Bj3}^2}} \tag{3}$$

X_{ij}^{FSM} can be obtained from Equation (1) after X_{ij}^d being decided using the synonym analysis software, such as semantic similarity computing and programming based on synonym forest [13].

2.2 Identifying Sharable Functional Components

An FECCM of products A and B can be built based on relations of components and functional elements as shown in Figure 5.
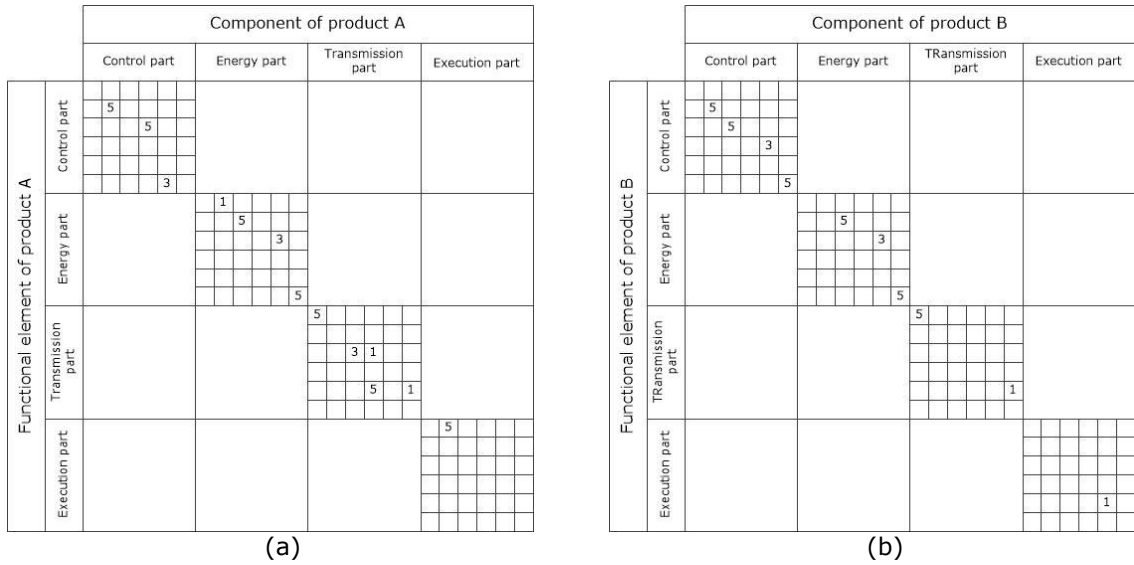

Figure 5: Functional element-component correlation matrix (FECCM). (a) product A, and (b) product B.

The CCSM can then be formed as follows.

$$[CCSM]_{mn} = [FECCM]_{im}^T \times [FESM]_{ij} \times [FECCM]_{jn} \tag{4}$$

The greater the value of element X in the CCSM, the higher the functional similarity between the *ith* component in product A and the *jth* component in product B, and the higher the possibility of the two components to be combined for a shared function in a multi-functional product. A bipartite graph is therefore constructed to search the optimal matches of components with the functional similarity, Figure 6 shows the process of searching optimal matches. Before searching for the optimal matches, the node must be assigned a value. 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 [3].

The CCSM can then be formed based on the optimal search shown in Figure 6, Figure 7 shows the CCSM of products A and B. 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 [19] or transformation principle and transformation facilitator [15] to guide the process. Components with the less similarity should be considered as independent parts.
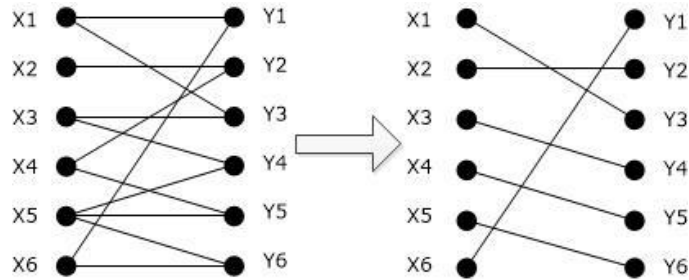
Figure 6: The process of searching the optimal matches.

Equation (5) is proposed to evaluate the use of space and material resources based on the number of components in a product.

$$I = 1 - \frac{\sum NC}{\sum NC_1 + \sum NC_2} \qquad (5)$$

Figure 7: Component-component similarity matrix (CCSM) of products A and B.

Where I denotes the degree of savings in resources of products. The molecule, $\sum NC$ is the total number of components in the new product, the denominator includes the total number of parts in the existing two products. The value of I is in between 0 and 1. A higher value of I represents the more resources saved.

3   CASE STUDY

The electric cleaning brush and shaver are two different cleaning products. A new multi-functional product is proposed to combine functions of both the brush and shaver using the proposed method. The main function of the electric shaver is to cut off the beard [12], while the electric cleaning brush is to separate stains [16]. Functional structures of the electric shaver and cleaning brush are shown in Figure 8. Functions of both products are to convert electrical energy into kinetic energy. Functions of the transmission part of both products are to transfer kinetic energy, and functions of the executive part are to transform the material into what the users wants. Functional elements are classified according to four parts of the technical system in Table 2.
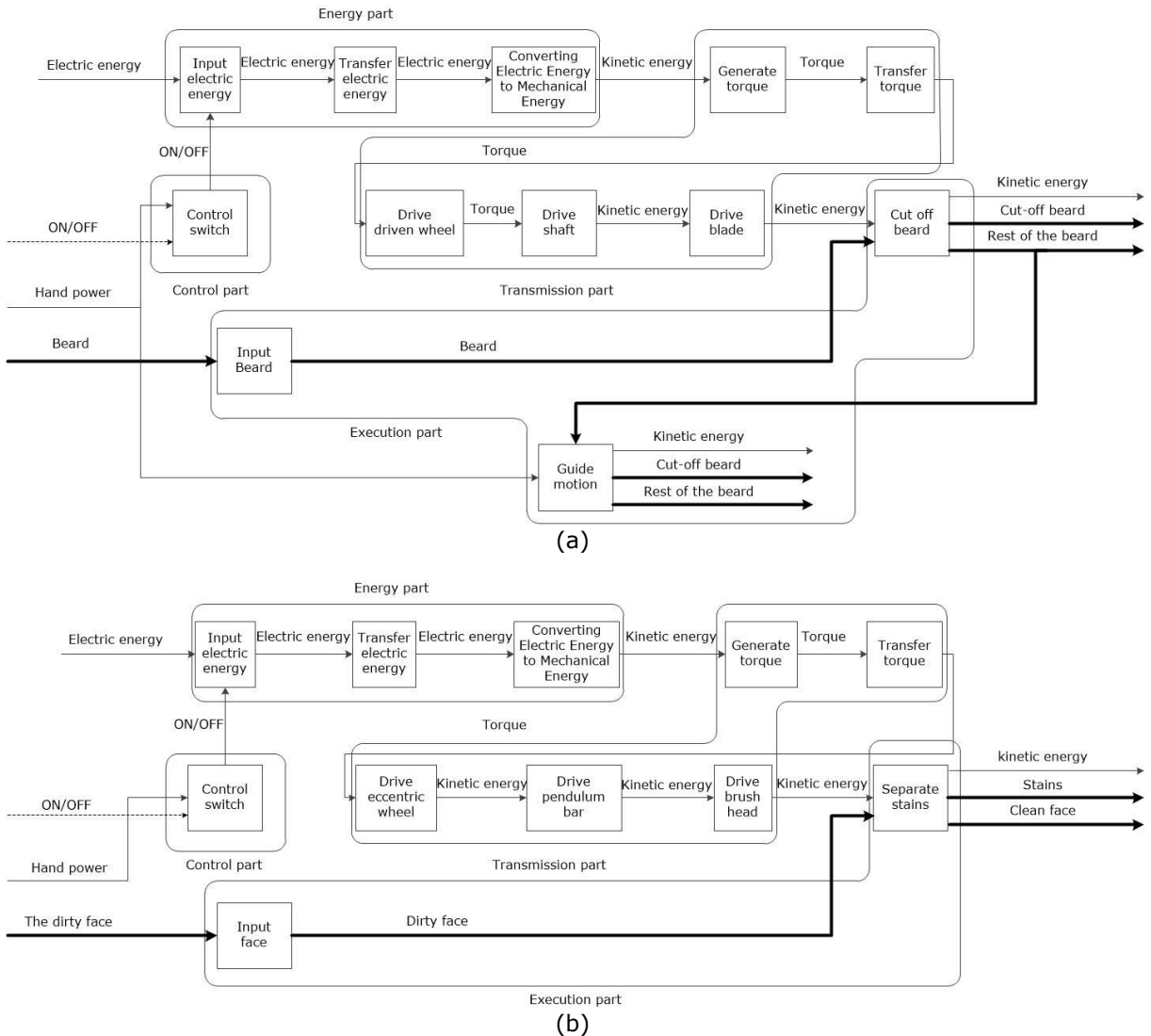

(a)

(b)

Figure 8: Functional structures of two products. (a) electric shaver, and (b) electric cleaning brush.

Part	Electric shaver	Electric cleaning brush
Control	Control switch	Control switch
Energy	Input electric energy, Transfer electric energy, Converting electric energy to mechanical energy	Input electric energy, Transfer electric energy, Converting electric energy to mechanical energy
Transmission	Generate torque, Transfer torque, Drive driven wheel, Drive shaft, Drive blade	Generate torque, Transfer torque, Drive eccentric wheel, Drive pendulum bar, Drive brush head
Execution	Input beard, Cut off beard, Guide motion	Input face, Separate stains

Table 2: Distribution of functional elements in four parts.

Weights of three flows are scored in four parts of the two products. A fuzzy number matrix of three flows in four parts of the electric shaver and cleaning brush is formed as shown in Figure 9.
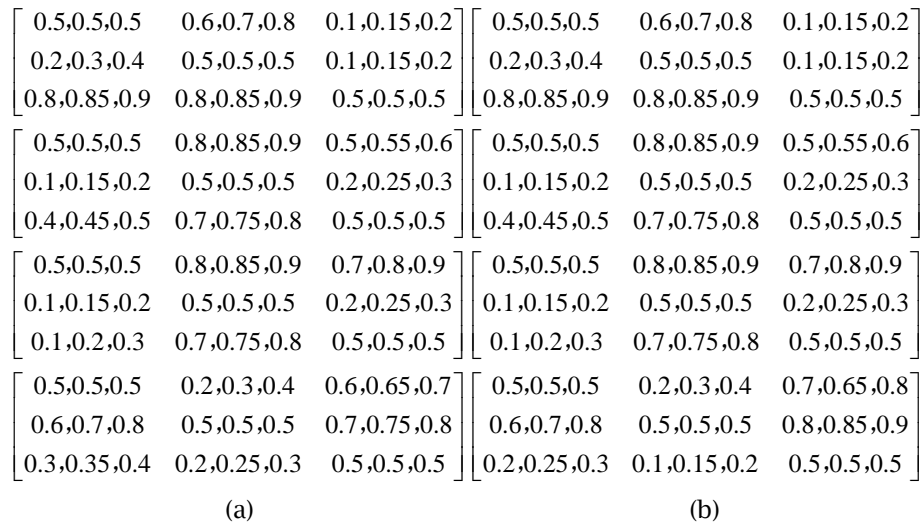
$$
\begin{bmatrix}
0.5,0.5,0.5 & 0.6,0.7,0.8 & 0.1,0.15,0.2 \\
0.2,0.3,0.4 & 0.5,0.5,0.5 & 0.1,0.15,0.2 \\
0.8,0.85,0.9 & 0.8,0.85,0.9 & 0.5,0.5,0.5
\end{bmatrix}
\begin{bmatrix}
0.5,0.5,0.5 & 0.6,0.7,0.8 & 0.1,0.15,0.2 \\
0.2,0.3,0.4 & 0.5,0.5,0.5 & 0.1,0.15,0.2 \\
0.8,0.85,0.9 & 0.8,0.85,0.9 & 0.5,0.5,0.5
\end{bmatrix}
$$

$$
\begin{bmatrix}
0.5,0.5,0.5 & 0.8,0.85,0.9 & 0.5,0.55,0.6 \\
0.1,0.15,0.2 & 0.5,0.5,0.5 & 0.2,0.25,0.3 \\
0.4,0.45,0.5 & 0.7,0.75,0.8 & 0.5,0.5,0.5
\end{bmatrix}
\begin{bmatrix}
0.5,0.5,0.5 & 0.8,0.85,0.9 & 0.5,0.55,0.6 \\
0.1,0.15,0.2 & 0.5,0.5,0.5 & 0.2,0.25,0.3 \\
0.4,0.45,0.5 & 0.7,0.75,0.8 & 0.5,0.5,0.5
\end{bmatrix}
$$

$$
\begin{bmatrix}
0.5,0.5,0.5 & 0.8,0.85,0.9 & 0.7,0.8,0.9 \\
0.1,0.15,0.2 & 0.5,0.5,0.5 & 0.2,0.25,0.3 \\
0.1,0.2,0.3 & 0.7,0.75,0.8 & 0.5,0.5,0.5
\end{bmatrix}
\begin{bmatrix}
0.5,0.5,0.5 & 0.8,0.85,0.9 & 0.7,0.8,0.9 \\
0.1,0.15,0.2 & 0.5,0.5,0.5 & 0.2,0.25,0.3 \\
0.1,0.2,0.3 & 0.7,0.75,0.8 & 0.5,0.5,0.5
\end{bmatrix}
$$

$$
\begin{bmatrix}
0.5,0.5,0.5 & 0.2,0.3,0.4 & 0.6,0.65,0.7 \\
0.6,0.7,0.8 & 0.5,0.5,0.5 & 0.7,0.75,0.8 \\
0.3,0.35,0.4 & 0.2,0.25,0.3 & 0.5,0.5,0.5
\end{bmatrix}
\begin{bmatrix}
0.5,0.5,0.5 & 0.2,0.3,0.4 & 0.7,0.65,0.8 \\
0.6,0.7,0.8 & 0.5,0.5,0.5 & 0.8,0.85,0.9 \\
0.2,0.25,0.3 & 0.1,0.15,0.2 & 0.5,0.5,0.5
\end{bmatrix}
$$

(a) (b)

Figure 9: Fuzzy number matrix of three flows in four parts of the both products. (a) electric shaver, and (b) electric cleaning brush.

Different products have different weights of flows. Weights of three flows in four parts of the electric shaver are obtained using the FOWA operator [17]: ω_{11}= (0.29, 0.19, 0.52), ω_{12}= (0.43, 0.18, 0.39), ω_{13}= (0.52, 0.17, 0.31), and ω_{14}= (0.31, 0.44, 0.25). Weights of three flows in four parts of the electric cleaning brush are obtained as: ω_{11}= (0.29, 0.19, 0.52), ω_{12}= (0.43, 0.18, 0.39), ω_{13}= (0.52, 0.17, 0.31), and ω_{14}= (0.34, 0.48, 0.18). Because the functional performance of these two products is at the same level, the similarity of these functional elements can be directly compared. Using Equations (1) and (3), an FESM of the electric shaver and cleaning brush can be obtained as shown in Figure 10.

FECCM of the electric shaver and cleaning brush can be built based on relations of components and functional elements as shown in Figure 11. The CCSM is obtained using Equation (4). Values in the matrix represent the similarity between components. Some components with the lower similarity have weaker substitutability. It is advisable to treat components with the similarity value

less than 0.4 as dissimilar. The CCSM of the electric shaver and cleaning brush is then normalized and filtered as shown in Figure 12. A bipartite graph is therefore constructed to search the optimal matches of components with the functional similarity, the value of bipartite graph is the degree of similarity of elements between electric shaver and cleaning brush, as shown in Figure 13. After the optimal matching, a list of sharable functional components can be obtained in Table 3. The value in this table shows degrees of the similarity.

	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
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	0.05	1	0.5	0.5		
Drive blade					0.32	0.05	0.5	1	1		
Input Beard										1	0.05
Cut off beard										0.05	0.75
Guide motion										0.32	0.35

Figure 10: FESM of the electric shaver and cleaning brush.

	Switch	Battery	Power circuit	Electric motor	Output shaft	Gear	Driven gear	Lever	Eccentric parts	Axis of rotation	Shell	Bracket	Blade	The Clippers
Control switch	5													
Input electric energy		5												
Transfer electric energy			5											
Converting Electric Energy to Mechanical Energy				5										
Generate torque				5	5									
Transfer torque					5									
Drive driven wheel						5								
Drive shaft							5							
Drive blade								3	3	5				
Input Beard												5		
Cut off beard												3	5	5
Guide motion											5			

(a)

	Switch	Battery	Power circuit	Electric motor	Output shaft	Eccentric wheel	Eccentric shaft	Pendulum trough	Swing rod	Connecting rod	Supporting parts	Shell	Brush head
Control switch	5												
Input electric energy		5											
Transfer electric energy			5										
Converting Electric Energy to Mechanical Energy				5									
Generate torque				5									
Transfer torque					5								
Drive eccentric wheel					5								
Drive pendulum bar						5	5	3					
Drive brush head									3	5	3		
Input face												5	3
Separate stains													5

(Row label group: *Functional element of electric cleaning brush*; column group: *Component of electric cleaning brush*)

(b)

Figure 11: FECCM of the two products. (a) electric shaver, and (b) 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
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

(Row group: *Component of electric shaver*; column group: *Component of electric cleaning brush*)

Figure 12: Normalized and filtered CCSM of electric shaver and cleaning brush.

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 rotation axis and eccentric shaft, may have some conflict problems if they are used as shared functional components. The TRIZ or transformation principle and transformation facilitator can be used to guide the design. Low-correlation components, such as blade and brush head, should be considered as separated parts.
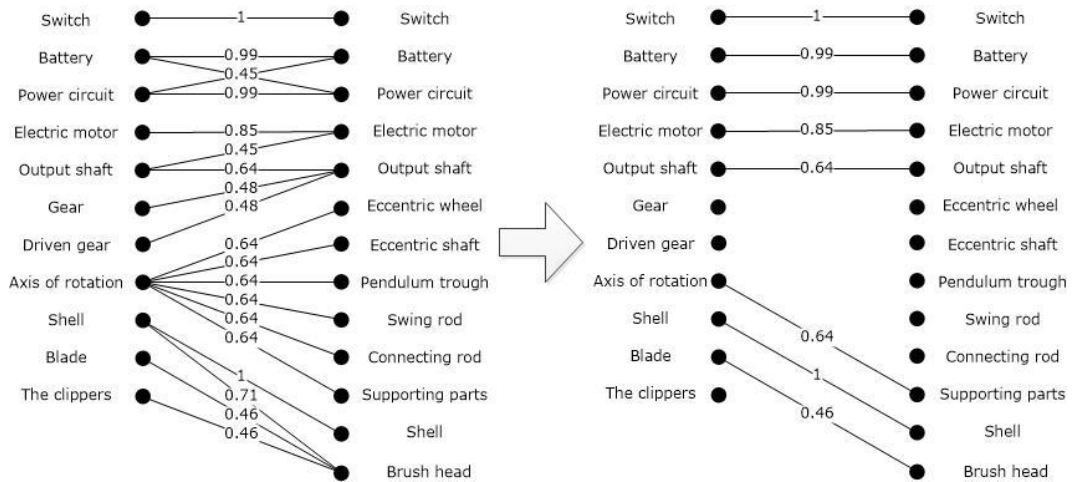
Figure 13: The process of searching the optimal match of electric shaver and cleaning brush.

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

Table 3: Sharable functional components.

Using Equation (5), $I = 1 - \dfrac{20}{13+14} = 0.26$, which shows that 26% of the components can be replaced to greatly save the space and material resources. After electric shaver and cleaning brush are integrated into a new multi-functional product, there is a new functional structure, the functional structure of the new multi-functional product is shown in Figure 14. The electric shaver has 12 functional elements, the electric cleaning brush has 11 functional elements, but the new multi-functional product has only 15 functional elements. Obviously, functional elements of the new multi-functional product are less than the sum of the two single product function elements. The product structure therefore is simplified.

4   CONCLUSIONS

Multi-functional products can save resources and provide users convenience. This paper proposed a method to search common components of different products in design of multi-functional products. The functional similarity of components in different products is searched using product function descriptions. A component-component similarity matrix (CCSM) is built by combining the functional element similarity matrix (FESM) and functional element-component correlation matrix (FECCM). 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. Further work is to apply the proposed method in design of different multi-functional products for the method improvement.
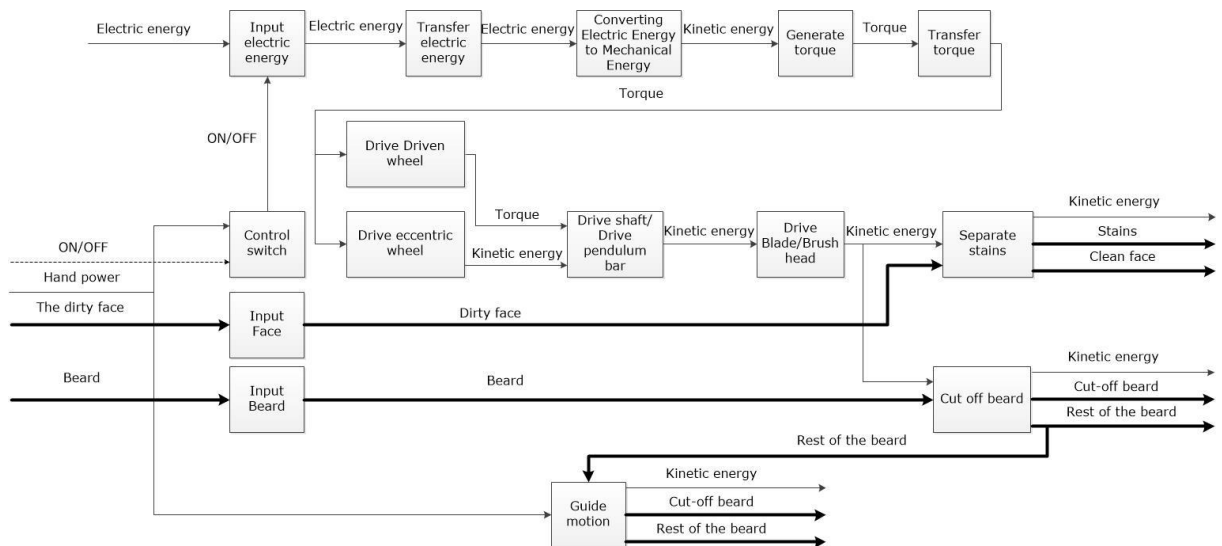

Figure 14: Functional structure of the new multi-functional product.

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