Title:
A Product Design Method Based on Functional Similarity

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Introduction:
In design activities, analogical sources can inspire designers to generate high-quality ideas. When multiple cases are retrieved, it is important to choose the appropriate one as an analogical source. Time and manpower are wasted if we traverse all cases. Meanwhile, it is difficult to ensure the generation of high-quality ideas if a random case is chosen to inspire the designer. Functions of a technical system are designed based on user needs[5]. Function is a description of the product's purpose, as well as the conversion between energy, materials, and information[2]. Similar user needs can be met by similar functions. The analogical source has a function that is more similar to the design problem; the design solution is closer to user needs. Therefore, this research will focus on selecting a case that is most similar in function to the design problem.

Functional description is in textual form, which is an abstraction of the principles of function. Functional description is composed of semantics and syntax, and the design intention in a certain design scenario can be accurately summarized by it[4]. Therefore, the text similarity between two standard functional descriptions can represent the similarity between the two functions. The calculation of text similarity is a fundamental research in computer science, which has been widely applied in various fields such as natural language processing, text clustering and classification, intelligent retrieval, automatic translation, and word meaning analysis [224]. However, there is a lack of a systematic method to calculate functional similarity. In order to solve the problem mentioned above, this paper first proposes a method for establishing standard functional models, which combines different types of functional models into a functional matrix and further transforms it into a standard vector. Secondly, a similarity calculation method for each element in the above functional model has been proposed. A transformable wheel is designed to verify the method.

Main Idea:
Establish the standard functional model
There are many types of functional descriptions, and a standard functional model helps to calculate functional similarity. The different conversion forms between input and output flows result in different types of functional descriptions, which can be classified into three types [4]:

- Qualitative functional description

This type of functional description mainly expresses the essential changes between the input to output flows. This expression form is verb+noun or verb+noun+prep/conj+noun, such as input liquid or convert thermal energy into electrical energy.

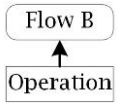
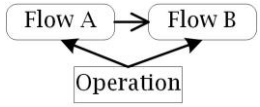
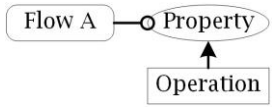
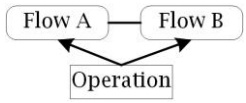
- Quantitative functional description

This type of functional description mainly expresses changes in the properties of the flow. The expression form is verb + noun + noun, such as reducing the volume of gas.

- Relationship transformation functional description

This type of functional description mainly expresses the changes in relationships between flows. This expression form is verb+noun+prep/conj+noun, such as absorb dust in the air.

There are four types of words in functional description: verbs, nouns, prep, and conj. Verbs refer to operations in functional description. Nouns refer to the flow and its properties, Preps, and cons refer to the relationship between flows and flows, and flows and properties. There are also functional relationships between operations and flows, operations and properties, which do not require preps or conjs to express. There are four types of functional models, as shown in Tab. 1.

No.	Functional models	Explanation
1		Operation acts on flow B
2		Under the action of operation, flow A is converted into flow B
3		Under the action of operation, the properties of flow A have changed
4		Under the action of operation, the relationship between flow A and flow B has changed

Tab. 1: Four types of functional models.

It is difficult to calculate the similarity between different types of functional models because they involve different elements and relationships. Therefore, this research proposes a standardized functional modeling method. Some elements and relationships exist in multiple functional models, while others only exist in one functional model. So a standardized functional modeling method should be able to take into account all situations. The relationship between elements must be taken into consideration. There are four elements in the four models, and five combinations of elements have relationships, so a standardized model should have nine factors. Among them are elements represented by text and relationships represented by presence or absence. Four different types of functional models are merged into one model and transformed into a matrix, further transformed into a vector, as shown in Fig. 1.

In Fig. 1, d_{11} represents flow A, d_{12} represents the relationship between flow A and flow B, d_{13} represents flow B, d_{21} represents the relationship between flow A and its property, d_{22} represents the relationship between operation and flow A, d_{23} represents the relationship between operation and flow B, d_{31} represents property, d_{32} represents the relationship between operation and property, and d_{33} represents operation. Several examples of functional models that transform symbols into matrices and vectors are shown in Tab. 2.

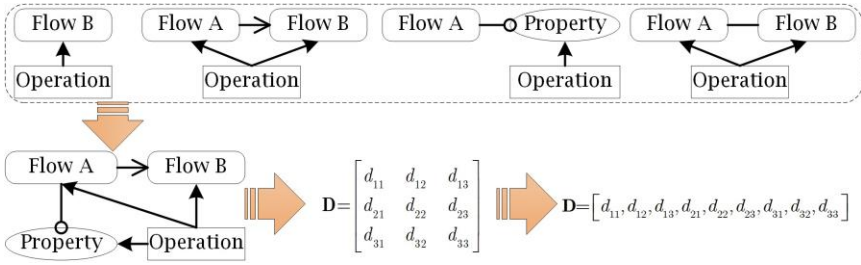


Fig. 1: Standardized functional modeling method.

Symbols	Matrices
Liquid → Input	$\begin{bmatrix} 0 & 0 & \text{liquid} \\ 0 & 0 & 1 \\ 0 & 0 & \text{input} \end{bmatrix}$
Thermal energy → Electrical energy; Convert	$\begin{bmatrix} \text{thermal energy} & \text{into} & \text{electrical energy} \\ 0 & 1 & 1 \\ 0 & 0 & \text{convert} \end{bmatrix}$
Gas — Volume; Reduce	$\begin{bmatrix} \text{gas} & 0 & 0 \\ \text{of} & 0 & 0 \\ \text{volume} & 1 & \text{reduce} \end{bmatrix}$
Dust — Air; Absorb	$\begin{bmatrix} \text{dust} & \text{in} & \text{air} \\ 0 & 1 & 1 \\ 0 & 0 & \text{absorb} \end{bmatrix}$

Tab. 2: Examples of functional models that transform symbols into matrices and vectors.

Calculate functional similarity

The similarity calculation between two functions can be transformed into the similarity calculation between two vectors based on the standardized process in Fig. 1. The similarity between two vectors can be calculated using the cosine theorem. There are vectors $\mathbf{D}_i=[d_{i1}, d_{i2},..., d_{i9}]$ and $\mathbf{D}_j=[d_{j1}, d_{j2},..., d_{j9}]$, and their similarity can be calculated by equation (1).

$$Sim(\mathbf{D}_i,\mathbf{D}_j)=\frac{\sum_{k=1}^{9} Sim(d_{ik},d_{jk})}{9} \tag{1}$$

Where, $Sim(d_{i2},d_{j2})$, $Sim(d_{i4},d_{j4})$, $Sim(d_{i5},d_{j5})$, $Sim(d_{i6},d_{j6})$, $Sim(d_{i8},d_{j8})$ represent the similarity of relationships in the functional model, which can be calculated by equation (2).

$$Sim(d_{ik},d_{jk})=\begin{cases}1, & \text{if } d_{ik}=d_{jk}\\ 0, & \text{if } d_{ik}\neq d_{jk}\end{cases} \quad k=2,4,6,8 \tag{2}$$

The similarity of $Sim(d_{i1},d_{j1})$, $Sim(d_{i3},d_{j3})$, and $Sim(d_{i9},d_{j9})$ is calculated using text similarity. Text similarity calculation based on semantic dictionaries is one of the most popular methods. There are various semantic dictionaries available, such as Wordnet, Mindnet, Framenet, Chinese Concept Dictionary, and Synonym Dictionary. Based on the Synonym Dictionary, the "HIT IR-Lab Tongyici Cilin" has been developed, which includes massive words, clear classification, easy calculation [3]. Therefore, it was

chosen as the basis for calculating text similarity. $Sim(d_{i1},d_{j1})$, $Sim(d_{i3},d_{j3})$, and $Sim(d_{i9},d_{j9})$ can be calculated by equation(3)-(7)[6].

- Two words are not on the same word tree

$$Sim(d_{ik},d_{jk}) = 1 \tag{3}$$

- Two words on the second layer branch of the word tree

$$Sim(d_{ik},d_{jk}) = 1 \times 0.65 \times \left[\cos n \times \frac{\pi}{180}\right]\left[\frac{n-m+1}{n}\right] \tag{4}$$

- Two words on the third layer branch of the word tree

$$Sim(d_{ik},d_{jk}) = 1 \times 1 \times 0.8 \times \left[\cos n \times \frac{\pi}{180}\right]\left[\frac{n-m+1}{n}\right] \tag{5}$$

- Two words on the fourth layer branch of the word tree

$$Sim(d_{ik},d_{jk}) = 1 \times 1 \times 1 \times 0.9 \times \left[\cos n \times \frac{\pi}{180}\right]\left[\frac{n-m+1}{n}\right] \tag{6}$$

- Two words on the fifth layer branch of the word tree

$$Sim(d_{ik},d_{jk}) = 1 \times 1 \times 1 \times 1 \times 0.96 \times \left[\cos n \times \frac{\pi}{180}\right]\left[\frac{n-m+1}{n}\right] \tag{7}$$

Where n represents the number of nodes in the branch layer, and m represents the distance between branches. Properties can be measured, so their similarity is related to their value. $Sim(d_{i7},d_{j7})$ can be calculated by equation (8).

$$Sim(d_{i7},d_{j7}) = \begin{cases} 0 & if\ \ d_{i7} \neq d_{j7} \\ 1 - \left| \dfrac{V_{imax} - V_{imin}}{V_{imax} + V_{imin}} - \dfrac{V_{jmax} - V_{jmin}}{V_{jmax} + V_{jmin}} \right| & if\ \ d_{i7} = d_{j7} \end{cases} \tag{8}$$

Where V_{imax} and V_{jmax} are the maximum values of d_{i7} and d_{j7} during function execution, V_{imin} and V_{jmin} are the minimum values.

Case study

Sprayer is a small-scale automatic plant protection machine that can spray pesticides. It has been widely used around the world[1]. The general sprayer is shown in Fig. 2.

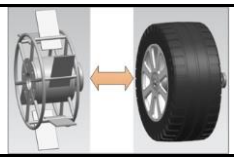
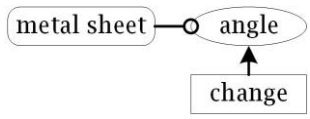
The wheels of general sprayer are suitable for flat fields. In paddy fields, the ground is muddy and special wheels with metal are necessary, As shown in Fig. 3.

Fig. 2: The general sprayer.

Fig. 3: The paddy sprayer.

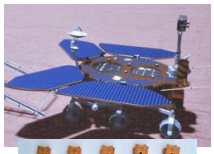
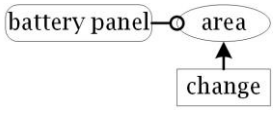
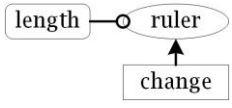
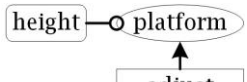
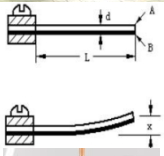
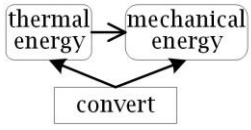
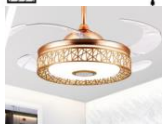
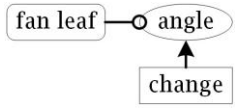
When the work scene switches between two types of fields, it is necessary to replace the wheels, which leads to wasting time. Therefore, a transformable wheel is needed to adapt to two types of fields. The function of transforming the state of two wheels is defined as changing the angle of the metal sheet. Its functional model has been established, as shown in Tab. 3.

Design problem	Functional model	Functional matrix

		$\begin{bmatrix} \text{metal sheet} & 0 & 0 \\ \text{of} & 0 & 0 \\ \text{angle} & 1 & \text{change} \end{bmatrix}$

Tab. 3: Functional model of transforming the state of two wheels.

Three are 5 cases that were retrieved from the library. Based on the method proposed above, its functional model and functional matrix can be established, and the functional similarity between these cases and the design problem can be calculated, as shown in Tab. 4.

No.	Cases	Functional models	Functional matrices	Similarities
1			$\begin{bmatrix} \text{battery panel} & 0 & 0 \\ \text{of} & 0 & 0 \\ \text{area} & 1 & \text{change} \end{bmatrix}$	0.808
2			$\begin{bmatrix} \text{ruler} & 0 & 0 \\ \text{of} & 0 & 0 \\ \text{length} & 1 & \text{change} \end{bmatrix}$	0.801
3			$\begin{bmatrix} \text{platform} & 0 & 0 \\ \text{of} & 0 & 0 \\ \text{height} & 1 & \text{adjust} \end{bmatrix}$	0.704
4			$\begin{bmatrix} \text{thermal energy} & \text{to} & \text{mechanical energy} \\ 0 & 1 & 1 \\ 0 & 0 & \text{convert} \end{bmatrix}$	0.111
5			$\begin{bmatrix} \text{fan leaf} & 0 & 0 \\ \text{of} & 0 & 0 \\ \text{angle} & 1 & \text{change} \end{bmatrix}$	0.881

Tab. 4: Functional models, functional matrices, and similarities of cases.

The functional symbol model and matrix model of the design problem are shown in Figure. 6 and Figure. 7, and its vector model is $\mathbf{D}_d$=[metal sheet, 0, 0, of, 0, 0, angle, 1, change]. The functional symbol model and matrix model of the fifth instance are shown in Table. 4, and its vector model is $\mathbf{D}_{c5}$=[fan leaf, 0, 0, of, 0, 0, angle, 1, change]. So, their functional similarity calculation can be converted into the similarity between vectors $\mathbf{D}_d$ and $\mathbf{D}_{c5}$. According to Equations (1)-(8), the similarity can be calculated as 0.881. The similarity calculation between other cases and design problems can also be calculated. The fifth case is used as an analogical source because it has the highest functional similarity to the design problem. Using it as an analogy source, the five results generated and the measurement results are shown in Fig. 4. Obviously, result 1 is the optimal choice, and its specific structure is shown in Fig. 5.

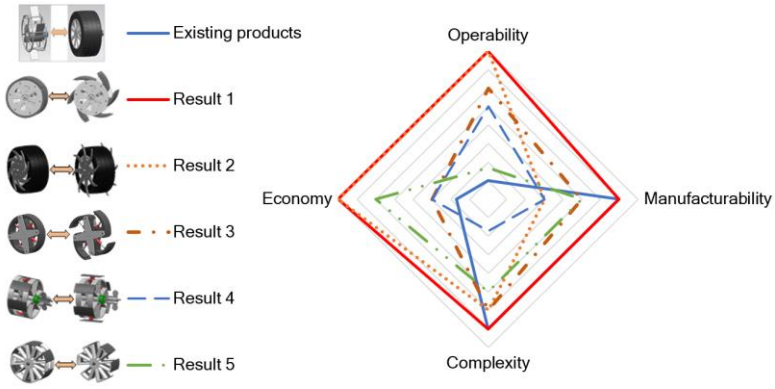


Fig. 4: The five results of analogical design

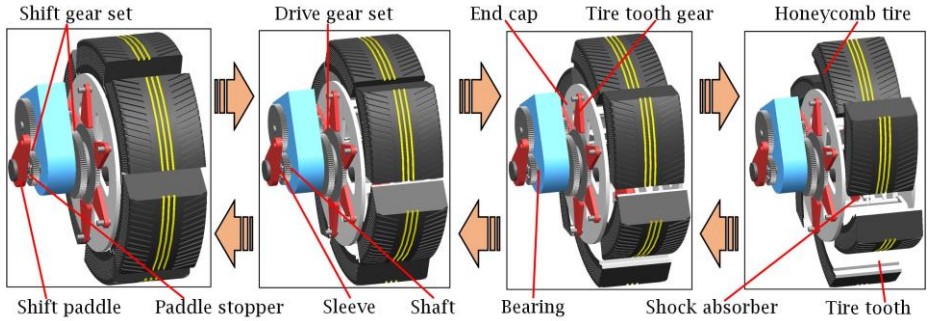


Fig. 5. The final design result.

Conclusion:

In this research, A product design method based on functional similarity is proposed to assist designers in selecting suitable analogical sources. A standardized functional modeling method has been proposed, where different types of functions can be represented. A similarity calculation method for each element in the above functional model has been proposed. A transformable tire is designed to verify the effectiveness of the proposed method. Future work will form a systematic process for the proposed method.

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