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Computer-Aided Design AND APPLICATIONS

A Product Design Method Based on Functional Similarity

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Abstract. Existing products that contain a large amount of design information and experience are often used as analogies when designing products, which will improve design efficiency. This is a challenge for designers to choose the most suitable analogy source from the case library. Function is the core of a product, and the similarity between functions often inspires creative ideas. This paper proposes a product design method based on functional similarity. An integrated functional modeling method is proposed, which combines four basic functional models into a unified symbolic model. The symbolic model is expressed in matrices and vectors for ease of calculation. A semantic-based method for calculating product functional similarity has been proposed. A transformable tire is designed using the proposed method in a case study.

Keywords: Product design, Functional similarity, Functional model, Functional matrix, Text similarity
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1 INTRODUCTION

In design activities, analogical sources can inspire designers to generate high-quality ideas. When multiple cases are retrieved, choosing the appropriate one as an analogical source is essential. Time and workforce are wasted if we traverse all cases. Meanwhile, it is not easy to ensure the generation of high-quality ideas if a random case is chosen to inspire the designer. The functions of a technical system are designed based on user needs[18]. A function describes the product's purpose and the conversion between energy, materials, and information[12]. Similar functions can meet similar user needs. 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 specific design scenario can be accurately summarized by it[15]. Therefore, the text similarity between two 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 [14]. However, a systematic method to calculate functional similarity needs to be improved. A modeling method for functional models has been proposed to solve the problem mentioned above. The functional models include symbol models, matrix models, and vector models. The advantage of the symbolic model is that it can represent the four basic functional models and information such as operations, flows, and properties in the functions. The advantage of matrix and vector models is that they can divide the symbol model into nine units and make the similarity of each unit easy to calculate. Text similarity is introduced to calculate the similarity of those text units. The calculation method for property values has also been proposed. Therefore, the innovative contribution of this paper is a proposal of an integrated model and a functional similarity calculation method based on it. The similarity between the two products can be calculated using the proposed method. The selection of analogy sources also has methodological support. Finally, a transformable wheel is designed to verify the method.

2 RELATED RESEARCH

Product design includes four stages: design planning, conceptual design, technical design, and detailed design[7]. The systematic design theory proposed by Pahl and Beitz provides a detailed description of the four stages mentioned above and explains how the functions are implemented step by step [20]. The V-shaped model in systems engineering is also widely used and has two arms. One arm represents the top-down decomposition of the functional level, and the other represents the bottom-up integration of the physical level [13]. The design space is divided into four domains in design order: requirements domain, functional domain, structural domain, and process domain. Each adjacent domain is mapped through a Z shape. The independence of functional requirements is beneficial for product design [10]. Gero [4] proposed the Function-Behavior-Structure(F-B-S) model, which uses behavior as a ladder to make the mapping from function to structure more reliable. Conversely, physical structure can be abstracted into function through behavior. Introducing environmental constraints in the F-B-S model will make it closer to reality [19]. The Structure-Behavior-Function (S-B-F) model can be used as a programming language to model complex systems[6]. Many ways of functional modeling have received widespread attention, and some computer-aided design software has also begun to focus on functional modeling[3]. The functional model that describes the purpose of a product is one of the most widely used models in design. Building a functional model will help to retrieve available cases and inspire analogical design [37]. These design methods all focus on function. People need the product's function rather than the product itself. Therefore, function is one of the most critical factors designers must consider.

Artificial intelligence technology is increasingly being applied in product design. Semi-supervised automatic methods are used to study the literature research on artificial intelligence in industrial design. Six intellectual cores were proposed, including (i) supply chain perspectives on product design and innovation, (ii) manufacturability and performance of the new product development, (iii) intelligent tools and systems for industrial design and engineering, (iv) applied intelligence for product and service innovation, (v) industry 4.0 technologies for design and manufacturing, and (vi) blockchain-enabled artificial intelligence in industry 4.0 [29]. The principles of artificial intelligence algorithms can be applied to the design, manufacturing, testing, and assembly processes of physical products. Moreover, it can build a design repository to support the entire development process [33]. Artificial intelligence is introduced in the preliminary design stage, conceptual design stage, problem definition stage, detailed design stage, and design communication stage [23]. The uncertainty of user needs will make the evaluation process of design solutions complex and costly [34]. The introduction of intelligent methods can reduce the complexity and cost of the evaluation process [25]. The research in this paper is mainly in the conceptual design stage, laying the foundation for intelligent selection of analog sources. The combination of artificial intelligence, computer-aided design, and computer-aided engineering can achieve the conceptual design of wheels [16]. However, it did not mention how to find similar cases to assist in design. Neural network algorithms can decode three-dimensional objects into one-dimensional space, which helps evaluate the similarity of objects[9]. How to obtain suitable cases from a functional perspective still needs to be studied. If artificial intelligence algorithms can be applied to measure function design, it will increase the number of product design results and reduce design costs.

The function is often not entirely new, and case-based reasoning is applying previous design experience or cases to solve new problems [24]. Cases with high availability can be accurately retrieved, which is helpful for the design process. The meaning of a product is to execute functions, and cases with similar functions are more likely to stimulate designers better. Cluster analysis is a popular data mining technique, and its application in case retrieval has attracted much attention [30]. The entire case library can be transferred to several smaller case libraries, where the cases are more similar. Therefore, by comparing with the design objectives, the most similar cases can be retrieved[36]. In product design, design cases with similar functions often play the role of heuristic design that inspires new ideas [8]. Cosine similarity measurement is widely used for screening potential targets from search results [26]. Functional description is in the form of text, so it is appropriate to measure functional similarity from the perspective of text.

Similarity is defined as the commonness between two text snippets. The greater the commonness, the higher the similarity [31]. The research focus of semantic similarity calculation is to score the degree of similarity between the meanings expressed in two texts [21]. An extended similarity measurement framework has been constructed to map features to the field of information theory. A single method can achieve similarity calculation, but the stacking method can improve computational performance [17]. The goal of semantic similarity calculation is database integration, machine translation, semantic search, query expansion, and text classification [2]. Patents contain descriptions of functions. Patent similarity measurement is a fundamental component of patent analysis, which can effectively obtain technical intelligence, detect infringement risks, and evaluate whether it meets innovation standards [32]. A semantic analysis method based on entity and semantic relationships is proposed to evaluate patent similarity [1]. It will help calculate functional similarity. Similarity calculation has been applied in many fields, such as rapid diagnosis of faults in power grids [35]. In life sciences, semantic similarity calculation and machine learning methods can be used to retrieve relevant background knowledge [11]. Functional similarity calculation is also applied in the field of the software supply chain, which can assist designers in finding available code in open-source libraries [27]. The similarity of short texts is an essential component of natural language, and the similarity of long sentences is also based on it [22]. The functional description is composed mainly of short text, so the similarity calculation involved in this research is based on short text. Therefore, there is a lack of a functional similarity calculation method for product design.

3 PROPOSED METHOD

3.1 Establish the Integrated Functional Model

There are many types of functional descriptions, and an integrated 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[15]:

- 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. This expression form is verb+noun+noun, such as reduce 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 Table 1.

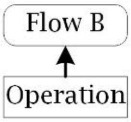
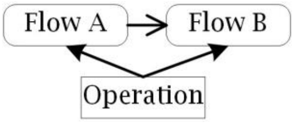
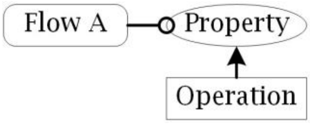
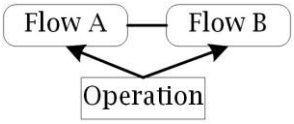
No.	Functional models	Explanation
1		Operation acts on flow B
2		Under the action of operation, flow A is converted into flow B
3		Under the action of operation, the properties of flow A have changed
4		Under the action of operation, the relationship between flow A and flow B has changed

Table 1: Four types of functional models.

The above four types of functional models include four elements: operation, flow A, flow B, and property, as well as five relationships between them, as shown in Table 2.

It is not easy to calculate the similarity between different types of functional models because they involve different elements and relationships. Therefore, this research proposes an integrated functional modeling method. Some elements and relationships exist in multiple functional models, while others only exist in one. An integrated functional modeling method should 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 an integrated model should have nine factors. Elements are represented by text, and relationships are represented by presence or absence. Four functional models are merged into one model and transformed into a matrix, further transformed into a vector, as shown in Figure 1.

category	Symbols	Explanation
Elements	Operation	Operation
	Flow A	Flow A
	Flow B	Flow B
	Property	Property of Flow
Relationships	➞	The effect of operation on a flow or a property
	→	The relationship between changes in flows
	—o	The attribution relationship between a flow and a property
	—	The binary relationship between two flows
		No relationship

Table 2: Explanation of functional elements and relationships.

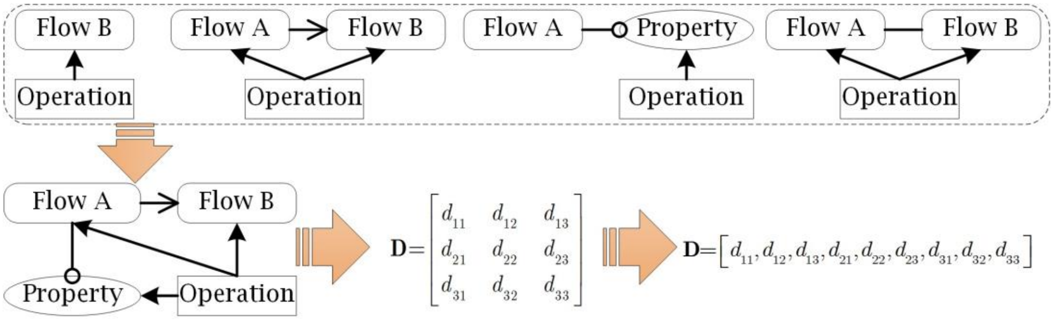


Figure 1: Integrated functional modeling method

In Figure 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 Table 3.

Symbols	Matrices
Liquid ↑ Input	$\begin{bmatrix} 0 & 0 & \text{liquid} \\ 0 & 0 & 1 \\ 0 & 0 & \text{input} \end{bmatrix}$

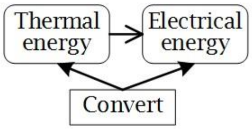
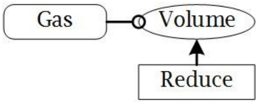
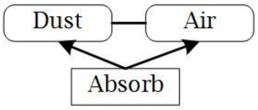
	$\begin{bmatrix} \text{thermal energy} & \text{into} & \text{electrical energy} \\ 0 & 1 & 1 \\ 0 & 0 & \text{convert} \end{bmatrix}$
	$\begin{bmatrix} \text{gas} & 0 & 0 \\ \text{of} & 0 & 0 \\ \text{volume} & 1 & \text{reduce} \end{bmatrix}$
	$\begin{bmatrix} \text{dust} & \text{in} & \text{air} \\ 0 & 1 & 1 \\ 0 & 0 & \text{absorb} \end{bmatrix}$

Table 3: Examples of functional models that transform symbols into matrices and vectors.

3.2 Calculate Functional Similarity

The similarity calculation between two functions can be transformed into the similarity calculation between two vectors based on the process in Figure 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 (3.1).

$$Sim(\mathbf{D}_i,\mathbf{D}_j) = \frac{\sum_{k=1}^{9} Sim(d_{ik},d_{jk})}{9} \tag{3.1}$$

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 (3.2).

$$Sim(d_{ik},d_{jk}) = \begin{cases} 1, & \text{if } d_{ik} = d_{jk} \\ 0, & \text{if } d_{ik} \neq d_{jk} \end{cases} \quad k = 2,4,6,8 \tag{3.2}$$

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. Various semantic dictionaries are 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, and easy calculation [14]. Therefore, it was chosen as the basis for calculating text similarity. The "HIT IR-Lab Tongyici Cilin" contains 77456 words, including 12 major categories, 95 medium categories, 1428 subcategories, 4026 word groups, and 17817 atomic word groups. Each atomic word group has a unique semantic code, and different semantic codes represent different synonym entries. These classifications adopt a hierarchical tree structure, with increasing levels representing a more detailed portrayal of word semantics. The tree structure of "Harbin Institute of Technology Cilin" is shown in Figure 2.

Different word tree layers have different encoding forms, with each word having an 8-digit encoding. The first digit is represented by a capital letter, representing the encoding of the first layer. The second digit is represented by a lowercase letter, representing the encoding of the second layer. The third and fourth digits are represented by decimal integers, representing the encoding of the third layer. The fifth digit is represented by a capital letter, representing the encoding of the fourth layer. The sixth and seventh digits are represented by decimal integers, representing the encoding of the fifth layer. The eighth digit is represented by "=", "#", and "@", representing the specific encoding of word classification. "=" represents "synonymous", and there are synonyms in the dictionary. "#" represents "related"; there are no synonyms in the dictionary, but there are related words. "@" represents "closed" or "independent," and there are no synonyms or related words in the dictionary [28].

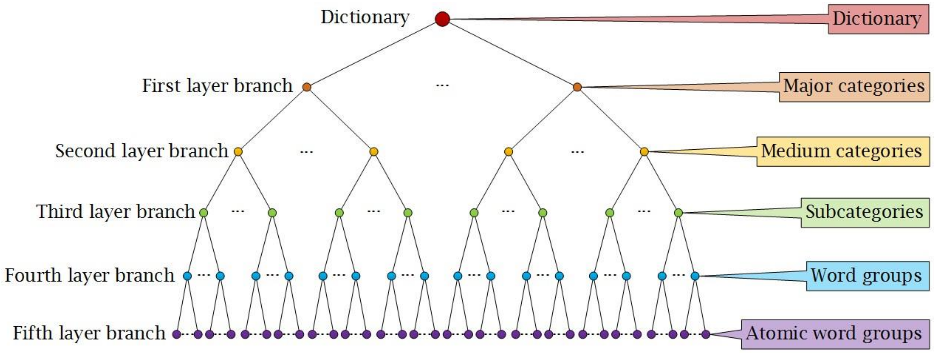


Figure 2: The tree structure of "Harbin Institute of Technology Cilin."

Based on "HIT IR-Lab Tongyici Cilin", $Sim(d_{i1},d_{j1})$, $Sim(d_{i3},d_{j3})$, and $Sim(d_{i9},d_{j9})$ can be calculated by Equation (3.3)-(3.7)[28].

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

$$Sim(d_{ik},d_{jk}) = 0.1 \tag{3.3}$$

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

$$Sim(d_{ik},d_{jk}) = 1\times 0.65\times\left[\cos n\times\frac{\pi}{180}\right]\left[\frac{n-m+1}{n}\right] \tag{3.4}$$

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

$$Sim(d_{ik},d_{jk}) = 1\times 1\times 0.8\times\left[\cos n\times\frac{\pi}{180}\right]\left[\frac{n-m+1}{n}\right] \tag{3.5}$$

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

$$Sim(d_{ik},d_{jk}) = 1\times 1\times 1\times 0.9\times\left[\cos n\times\frac{\pi}{180}\right]\left[\frac{n-m+1}{n}\right] \tag{3.6}$$

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

$$Sim(d_{ik},d_{jk}) = 1\times 1\times 1\times 1\times 0.96\times\left[\cos n\times\frac{\pi}{180}\right]\left[\frac{n-m+1}{n}\right] \tag{3.7}$$

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 (3.8).

$$Sim(d_{i7},d_{j7}) = \begin{cases} 0 & if\ d_{i7}\neq d_{j7} \\ 1-\left|\frac{V_{imax}-V_{imin}}{V_{imax}+V_{imin}} - \frac{V_{jmax}-V_{jmin}}{V_{jmax}+V_{jmin}}\right| & if\ d_{i7}=d_{j7} \end{cases} \tag{3.8}$$

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.

4 CASE STUDY

Sprayer is a small-scale automatic plant protection machine that can spray pesticides. It has been widely used around the world[5]. The general sprayer is shown in Figure 3.

Figure 3: The general sprayer.

The wheels of the general spray are suitable for walking in flat fields, not in paddy fields. The roads in the paddy field are muddy, and the shape of the wheels is often irregular. The paddy sprayer is shown in Figure 4.

Figure 4: The paddy sprayer.

When the work scene switches between two types of fields, the wheels must be replaced, which wastes time. Therefore, a transformable wheel is needed to adapt to both types of fields. The new wheels need to adapt to two different usage environments. The general sprayer in Figure 3 is used in dry fields. The undulating height of the road surface is 0-10cm, the friction coefficient of the road surface is 0.7-1, and the depth of crops is 12-16cm. The pad sprayer in Figure 4 is used in a paddy field. The undulating height of the road surface is 0-20cm, the friction coefficient of the road surface is 0.3-1, the water surface height is 4-5cm, and the depth of crops is 12-16cm. In order to adapt to both environments, design problems are defined as how to achieve changes in the shape of two types of wheels. As shown in Figure 5.

The function of transforming the state of two wheels is defined as changing the angle of the metal sheet. This is the verb+noun+noun form of functional description. The proposed method can be used to visualize it more clearly. Its functional symbol model has been established, as shown in Figure 6. The symbol model clearly shows the relationship between operation, flow, and property in the function. To facilitate the calculation of the similarity between new functions and existing cases, the proposed method should be applied to transform the symbol model into the matrix model. The matrix model of the design problem can be obtained according to the proposed method, as shown in Figure 7.

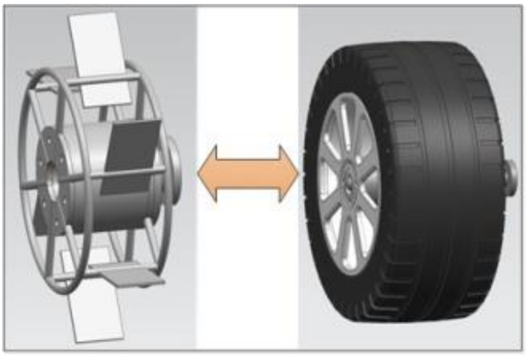


Figure 5: Changes in two types of wheels.

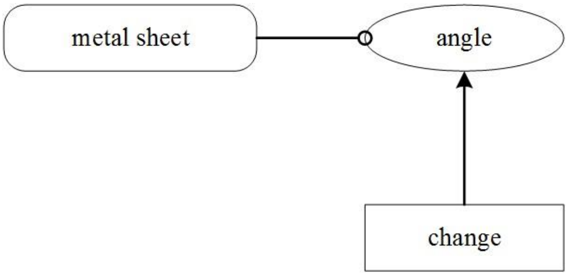


Figure 6: Symbol model of design problem

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

Figure 7: Matrix model of design problem.

Figures 6 and 7 show the functional symbol model and matrix model of the design problem, and its vector model is $\mathbf{D}_d$=[metal sheet, 0, 0, of, 0, 0, angle, 1, change]. Table 4 shows the solar panel of the Mars rover as a case to calculate its functional similarity with the design problem.

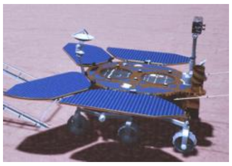
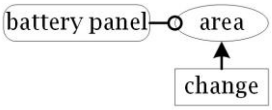
The solar panel	Symbol model	Matrix model
		$\begin{bmatrix} \text{battery panel} & 0 & 0 \\ \text{of} & 0 & 0 \\ \text{area} & 1 & \text{change} \end{bmatrix}$

Table 4: Symbol model and matrix model of the solar panel.

The vector model of the solar panels 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 (3.1)-(3.8), the similarity can be calculated. As shown in Equation (4.1).

$$Sim(\mathbf{D}_{d},\mathbf{D}_{c5}) = \frac{\sum_{k=1}^{9} Sim(d_{dk}, d_{jc5k})}{9} = \frac{7.27}{9} = 0.808 \tag{4.1}$$

In addition to the solar panel, there are four cases were retrieved from the library. The similarity between any case that can establish an integrated functional model and the design problem can be calculated. The sources of these cases are worth studying. The cases can be from papers, patents, shopping websites, or companies. Another work being done by the authors of this paper is to establish a cases library where cases are represented by symbol, matrix, and vector models. The mentioned cases were selected from the unfinished case library. The selection of cases was not mentioned in detail. The main innovative contribution of this paper is to illustrate how functional similarity calculation is implemented. Based on the proposed method, the functional and matrix models of the four cases can be established, and the functional similarity between these cases and the design problem can be calculated, as shown in Table 5.

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. Analogy design is the process of applying case structures to design problems. It is not easy to directly map between structures. It is necessary to convert the structural model of the case into a behavioral model and then convert the behavioral model into the design problem. The above process is shown in Figure 8.

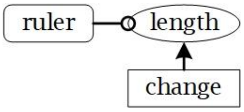
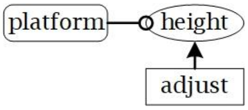
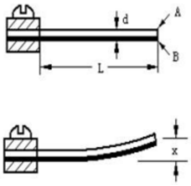
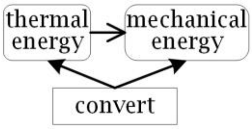
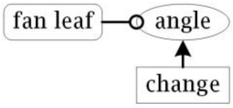
No.	Cases	Symbol models	Matrix models	Similarities
1			$\begin{bmatrix} \text{ruler} & 0 & 0 \\ \text{of} & 0 & 0 \\ \text{length} & 1 & \text{change} \end{bmatrix}$	0.801
2			$\begin{bmatrix} \text{platform} & 0 & 0 \\ \text{of} & 0 & 0 \\ \text{height} & 1 & \text{adjust} \end{bmatrix}$	0.704
3			$\begin{bmatrix}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

Table 5: Symbol models, matrix models, and similarities of cases.

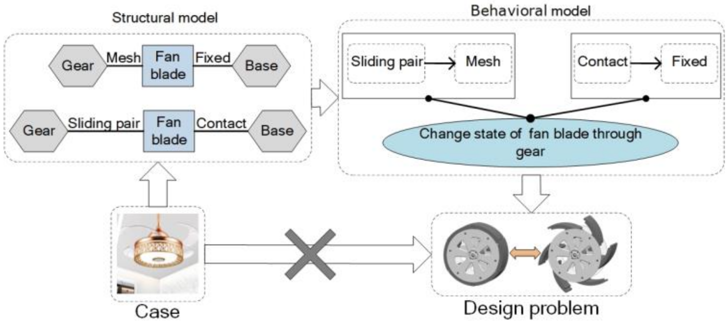


Figure 8: Analogy design process.

Using the electric fan light as the analogy source, a total of five results are generated, as shown in Table 6.

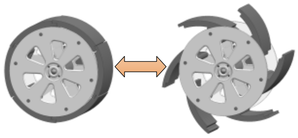
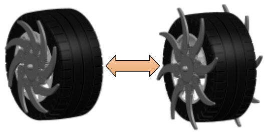
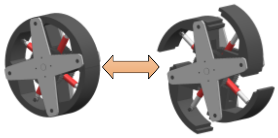
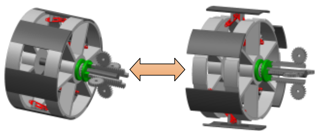
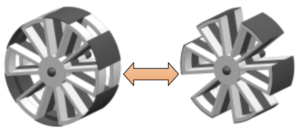
No.	Design results	Explanation of design results
1		Six tire teeth rotate along a fixed axis driven by a gear mechanism, and the angle between the tire teeth and the wheel hub changes.
2		Eight supporting teeth rotate along a fixed axis driven by the gear mechanism, and the supporting teeth can be higher or lower than the tire's surface.
3		The tire's surface is divided into four parts, each of which rotates along a fixed axis driven by the gear mechanism and cylinder.
4		The distance between two base wheels changes driven by gears and racks, and the height of the middle tire's surface also changes.
5		The gear mechanism drives the angle change between the intermediate wheel and the base wheel, changing the contact between the tire and the ground.

Table 6: The five results of analogical design.

In the unfolding state of the second design result, the contact surface between the supporting teeth and the ground is small. The supporting teeth must be made of high-performance materials, increasing manufacturing costs. In the unfolding state of the third design result, the wheel movement becomes step by step. It only makes contact with the ground four times in one rotation, which can cause significant vertical undulations in the vehicle and damage farmland and equipment. The structure of the fourth design result is complex and requires high machining accuracy. The gear rack structure may lead to a sizeable axial size. The fifth design result requires rotating the intermediate wheel along its axis, which has a larger size and a more complex transmission method. To evaluate the results, we invited three designers with engineering experience to measure the operability, manufacturability, complexity, and economy of the five results and existing products. Compare each indicator with each other and select the important one, as shown in Table 7.

Indicators	Operability	Manufacturability	Complexity	Economy
Operability	Operability	Operability	Operability	Operability
Manufacturability		Manufacturability	Manufacturability	Manufacturability
Complexity			Complexity	Economy
Economy				Economy

Table 7: Comparisons for the importance of indicators.

The number of times these indicators appear in Table 7 represents their importance, and the weights of these indicators can be calculated. Table 8 shows the specific explanations and weights of these indicators. Table 9 shows the standards for measuring scores of these indicators.

Indicators	Weight
Operability	0.4
Manufacturability	0.3
Complexity	0.1
Economy	0.2

Table 8: Weight of indicators.

Score	Operability	Manufacturability	Complexity	Economy
1	very weak	very weak	very strong	very weak
3	weak	weak	strong	weak
6	strong	strong	weak	strong
9	very strong	very strong	very weak	very strong

Table 9: Measurement score.

The reviewers measure the product based on the above rules. The measurement results are shown in Figure 9.

The weight can be included in Equation (4.2).

$$V = 0.4OP + 0.3MA + 0.1CO + 0.2EC \tag{4.2}$$

Where V represents the final score of the product, OP represents the score of operability, MA represents the score of manufacturability, CO represents the score of complexity, and EC represents the score of economy.

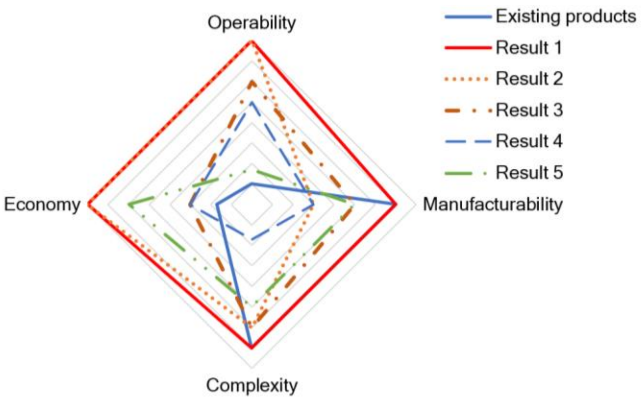


Figure 9: The measurement results.

According to the scores in Figure. 8 and Equation (4.2), the final scores for the existing product and five results can be calculated as 3.54, 7.60, 6.30, 5.10, 3.67, and 3.88. Obviously, result 1 in is the optimal choice, and its specific structure is shown in Figure 10.

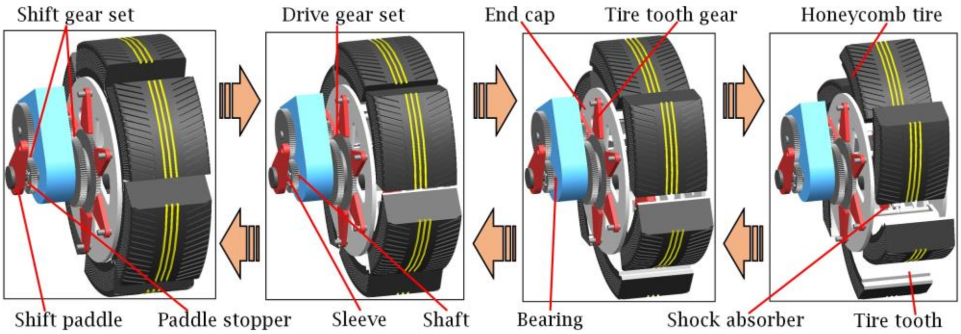


Figure 10: The final design result.

5 CONCLUSIONS

Cases that have similar functions to design problems can inspire creative ideas. In this research, A product design method based on functional similarity is proposed to assist designers in selecting suitable analogical sources. An integrated functional modeling method has been proposed, where different functions can be represented by symbol matrix and vector models. 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. The proposed method can quickly find the optimal analogy source, improve design efficiency, and reduce dependence on designer experience.

Classic design methods include systematic design, axiomatic design, quality function deployment, and theory of invention problem-solving. These design methods are very effective in product functional planning, architecture implementation, requirement analysis, and contradiction resolution. This paper's transformable wheels design is based on these design methods. The introduction of the methods proposed in this paper can further improve these methods, especially in the functional design stage. This is a crucial and challenging step in the design process of finding suitable analogs. The introduction of functional similarity calculation has solved this problem and provided methodological support for designers.

The integrated functional model proposed in this paper includes operations, flows, and properties. Mechanical products contain these factors. The example applied in the paper is a mechanical wheel. Its function is more easily expressed using the mentioned factors. So, the proposed method in this paper is more suitable for mechanical products with apparent functional factors. Some other products, such as handicrafts and software, sometimes have functions that are not easily expressed using these factors. Therefore, they are currently not suitable for the proposed method. Anyway, the proposed method also has certain limitations. It has mainly made efforts in similarity calculation. It relies on case libraries, and the modeling process has a certain degree of subjectivity. The functional model of nonmechanical products still needs to be studied. Future research will focus on case library construction and automated modeling software development suitable for various product types.

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REFERENCES

[1] An, X.; Li, J.; Xu, S.; Chen, L.; Sun, W.: An improved patent similarity measurement based on entities and semantic relations, Journal of Informetrics, 15(2), 2021, 101135. https://doi.org/10.1016/j.joi.2021.101135
[2] Chandrasekaran, D.; Mago, V.: Evolution of semantic similarity-a survey. ACM Computing Surveys (CSUR), 54(2), 2021, 1-37. https://doi.org/10.1145/3440755
[3] Erden, M.-S.; Komoto, H.; Beek, T.-J.; D'Amelio, V.; Echavarria, E.; Tomiyama, T.: A review of function modeling: Approaches and applications, AIEDAM, 22(2), 2008, 147-169. https://doi.org/10.1017/S0890060408000103
[4] Gero, J.-S.; Kannengiesser, U.: The situated function-behaviour-structure framework, Design Studies, 25(4), 2004, 373-391. https://doi.org/10.1016/j.destud.2003.10.010
[5] Ghafoor, A.; Khan, F.; Khorsandi, F.; Khan, M.; Nauman, H.; Farid, M.: Development and evaluation of a prototype self-propelled crop sprayer for agricultural sustainability in small farms, sustainability, 14(15), 2022, 9204. https://doi.org/10.3390/su14159204
[6] Goel, A.-K.; Spencer, R.; Swaroop, V.: Structure, behavior, and function of complex systems: The structure, behavior, and function modeling language, AIEDAM, 23(1), 2009, 23-35. https://doi.org/10.1017/S0890060409000080
[7] Hsiao, S.–W; Chou, J.-R.: A creativity-based design process for innovative product design, International Journal of Industrial Ergonomics, 34(5), 2004, 421-443. https://doi.org/10.1016/j.ergon.2004.05.005
[8] Hwang, D.; Park, W.: Design heuristics set for X: A design aid for assistive product concept generation, Design Studies, 58, 2018, 89-126. https://doi.org/10.1016/j.destud.2018.04.003
[9] Jenis, J.; Ondriga, J.; Hrcek, S.; Brumercik, F.; Cuchor, M.; Sadovsky, E.: Engineering applications of artificial intelligence in mechanical design and optimization, Machines, 11(6), 2023, 577. https://doi.org/10.3390/machines11060577

[10] Kulak, O.; Cebi, S.; Kahraman, C.: Applications of axiomatic design principles: A literature review, Expert Systems with Applications, 37(9), 2010, 6705-6717. https://doi.org/10.1016/j.eswa.2010.03.061
[11] Kulmanov, M.; Smaili, F.-Z.; Gao, X.; Hoehndorf, R.: Semantic similarity and machine learning with ontologies, Briefings in Bioinformatics, 22(4), 2021, bbaa199. https://doi.org/10.1093/bib/bbaa199
[12] Kuttig, D.: Potential and limits of functional modelling in the CAD process, Research in Engineering Design, 5(1), 1993, 40-48. https://doi.org/10.1007/BF01608396
[13] Li, Q.; Wei, H.; Yu, C.; Wang, S.-S.: Data and model-based triple V product development framework and methodology, Enterprise Information Systems, 16(5), 2022, 1867900. https://doi.org/10.1080/17517575.2020.1867900
[14] Li, Y.; Su, L.; Chen, J.; Yuan, L.: Semi-supervised learning for question classification in CQA, Natural Computing, 16, 2017, 567–577. https://doi.org/10.1007/s11047-016-9554-5
[15] Liu, W.; Tan, R.; Cao, G.; Yu, F.; Li, H.: Creative design through knowledge clustering and case-based reasoning, Engineering with Computers, 36, 2020, 527-541. https://doi.org/10.1007/s00366-019-00712-5
[16] Majchrák, M.; Kohár, R.; Kajan, J.; Skyba, R.: 3d meshing methods of ball-rolling bearings, Transportation Research Procedia, 40, 2019, 784–791. https://doi.org/10.1016/j.trpro.2019.07.111
[17] Martinez, G.-J.: A comprehensive review of stacking methods for semantic similarity measuremen, Machine Learning with Applications, 10, 2020, 100423. https://doi.org/10.1016/j.mlwa.2022.100423
[18] Miles, L.-D.: Techniques of value analysis and engineering, Miles Value Foundation, Washington DC, 2015.
[19] Mohammed, O.-M, Shammari, A.-Z.: Function modeling in engineering design: approaches and methods, Technium: Romanian Journal of Applied Sciences and Technology, 2(7), 2020, 222-239. https://doi.org/10.47577/technium.v222i2.1790
[20] Pahl, G.; Beitz, W.: Engineering Design: A Systematic Approach, Springer Science & Business Media, London, 2013.
[21] Pirro, G.; Euzenat, J.: A feature and information-theoretic framework for semantic similarity and relatedness, The Semantic Web – ISWC 2010, 615-630. https://dx.doi.org/10.1007/978-3-642-17746-0_39.
[22] Prakoso, D.-W.; Abdi, A.; Amrit, C.: Short text similarity measurement methods: a review, Soft Computing, 25, 2021, 4699-4723. https://doi.org/10.1007/s00500-020-05479-2
[23] Pranav, M.-K.; Ademir, V.; Alison, O.: Mapping artificial intelligence-based methods to engineering design stages: a focused literature review, AIEDAM, 37, 2023, e25. https://doi.org/10.1017/S0890060423000203
[24] Relich, M.; Pawlewski, P.: A case-based reasoning approach to cost estimation of new product development, Neurocomputing, 272, 2018, 40–45. https://doi.org/10.1016/j.neucom.2017.05.092
[25] Romeo, L.; Loncarski, J.; Paolanti, M.; Bocchini, G.; Mancini, A.; Frontoni, E.: Machine learning-based design support system for the prediction of heterogeneous machine parameters in industry 4.0, Expert Systems with Applications, 140, 2020, 112869. https://doi.org/10.1016/j.eswa.2019.112869
[26] Song, K.; Kim, K.; Lee, S.: Identifying promising technologies using patents: A retrospective feature analysis and a prospective needs analysis on outlier patents, Technological Forecasting and Social Change, 128, 2018, 118-132. https://doi.org/10.1016/j.techfore.2017.11.008
[27] Sun, W.; Shan, Z.; Liu, F.; Li, X.; Qiao, M.; Zhang, C.: Software supply chain analysis based on function similarity, In Journal of Physics: Conference Series, 1601(5), 2020, 052020. https://doi.org/10.1088/1742-6596/1601/5/052020

[28] Tian, J.; Zhao, W.: Words similarity algorithm based on Tongyici Cilin in semantic web adaptive learning system, Journal of Jilin University (Information Science Edition), 28(6), 2010, 602-608. https://doi:10.3969/j.issn.1671-5896.2010.06.011
[29] Tsang, Y.-P.; Lee, C.-K.-M.: Artificial intelligence in industrial design: A semi-automated literature survey, Engineering Applications of Artificial Intelligence, 112, 2022: 104884. https://doi.org/10.1016/j.engappai.2022.104884
[30] Tseng, H.-E.; Chang, C.-C.; Chang, S.-H.: Applying case-based reasoning for product configuration in mass customization environments, Expert Systems with Applications, 29(4), 2005, 913-925. https://doi.org/10.1016/j.eswa.2005.06.026
[31] Wang, J.; Dong, Y.: Measurement of text similarity: a survey, Information, 11(9), 2020, 421. https://doi.org/10.3390/info11090421
[32] Wang, X.; Ren, H.; Chen, Y.; Liu, Y.; Qiao, Y.; Huang, Y.: Measuring patent similarity with SAO semantic analysis. Scientometrics, 121(1), 2019, 1–23. https://doi.org/10.1007/s11192-019-03191-z
[33] Williams, G.; Meisel, N.-A.; Simpson, T.-W.; McComb, C.: Design for artificial intelligence: proposing a conceptual framework grounded in data wrangling, Journal of Computing and Information Science in Engineering, 22(6), 2022, 060903. https://doi.org/10.1115/1.4055854
[34] Wu, J.; Xing, B.; Si, H.; Jian, D.; Wang, J.; Zhu, Y.; Liu, X.: Product design award prediction modeling: Design visual aesthetic quality assessment via DCNNs, IEEE Access 8, 2020, 211028-211047. https://doi.org/10.1109/ACCESS.2020.3039715
[35] Zhang, C.; Yuan, X.; Shi, M.; Yang, J.; Miao, H.: Fault location method based on SVM and similarity model matching, Mathematical Problems in Engineering, 2020, 1-9. https://doi.org/10.1155/2020/2898479
[36] Zhu, G.-N.; Hu, J.; Qi, J.; Ma, J.; Peng, Y.-H.: An integrated feature selection and cluster analysis techniques for case-based reasoning, Engineering Applications of Artificial Intelligence, 39, 2015, 14-22. https://doi.org/10.1016/j.engappai.2014.11.006
[37] Zhu, G.-N.; Ma, J.; Hu, J.: Evaluating biological inspiration for biologically inspired design: An integrated DEMATEL-MAIRCA based on fuzzy rough numbers, International Journal of Intelligent Systems, 36(10), 2021, 6032-6065. https://doi.org/10.1002/int.22541