Agile Innovation Process Model Based on Computer-Aided Patent Knowledge Mining and Functional Analogy

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Abstract. As the variability and timeliness of customer demands pose new challenges to traditional design methods, it is urgent for a new innovative design method to meet the rapid and agile requirements of new product. Therefore, this paper proposed an agile innovation process model based on computer-aided patent knowledge mining and function analogy by combining computer-aided patent knowledge mining with product function analogy. First, the text information in the patent is excavated through computer assistance and stored in the form of functional structure and functional model. Second, the customer demand is analyzed and the functional decomposition is carried out. Then the functional structure of the new product is established in the form of a functional base. Third, similar functional structures and functional models are retrieved among the functional structures and functional models abstracted in the patent. Fourth, the functional design method of functional similarity matrix and computer-aided data processing is used in this paper. Finally, the final agile innovative design plan is obtained by solving the problems existing in the new product function model through analyzing the available resource analysis and material-field model analysis of TRIZ. In order to prove the scientificity and effectiveness of the proposed method, it is verified by the solar panel natural wind dust removal system in this paper.

Keywords: Patent knowledge mining, Computer-aided innovation design, Functional analogy, Functional structure, Functional model.
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1 INTRODUCTION

With the development of the knowledge network economy, the in-depth integration of innovative design and new technology has injected new momentum into the sustainable innovation and development of enterprises, which has become a new driving force leading the industrial revolution [13]. After entering the 21st century, competition in the product market has further intensified. A new design method is urgently needed to meet the agile and innovative design of new product. Product agile innovation design is an innovation-intensive process that requires a lot of knowledge and design experience [27], even cross-industry and cross-disciplinary knowledge as a resource for problem-solving. As the biggest knowledge provider, patent information plays an irreplaceable role inspiring designer in the conceptual design stage [9]. However, how to quickly and effectively dig out patent knowledge and apply it to the agile innovative design of products is an urgent problem to be solved.

Patent knowledge is mainly expressed in the form of natural language. However, large patent texts cannot quickly and effectively assist in innovative design [18]. Therefore, it is necessary to quickly dig out patent knowledge and turn it into usable knowledge for the agile and innovative design of products. Patent knowledge includes two parts: surface patent knowledge and deep patent knowledge. The surface patent knowledge can be expressed intuitively and can be expressed in a formal way, which is convenient for sharing and transmission. Deep patent knowledge is obscure and difficult to transform, but it directly affects the innovation and competitiveness of the designer or enterprise [4], [12]. At this stage, the research on the mining of patent knowledge mainly includes auxiliary innovation based on TRIZ theory and auxiliary innovation based on applied statistical methods. The former relies too much on the designer's own design experience, while the latter cannot effectively obtain and use the design knowledge in the patent to assist the designer in innovation. In recent years, with the rise of computer-aided design technology and machine learning technology, these tools have been widely used in the research and development of new products, manufacturing systems, and process-oriented design process. At the same time, the application of computer-aided design can improve the design quality of product [15], [19]. Therefore, patent knowledge mining is gradually developing in the direction of deep mining with unstructured data as the data source. Liu and his team [8] used machine learning and combined with functional language to mark the patent text. This method digs out the functional information in the patent text. Wang et al. [23], [24] used natural language understanding techniques such as lexical analysis, syntactic analysis, and semantic analysis to extract technical feature information from patents. Literature [30], [6] used verbs and noun phrases in patents to extract features of innovation levels. And they combined the cosine similarity theorem and vector space model to mine patent knowledge. Using computer-assisted patent mining have played a certain role in the analysis of patent texts. However, it is still difficult to transform the excavated text knowledge into functional knowledge for the agile innovative design of product.

Aiming at the problem that it is difficult to directly apply textual knowledge in patents to the agile innovative design of product, this paper combines computer-aided patent knowledge mining with the establishment of functional model and functional structure in TRIZ tools [16], [21]. Based on this, this research hopes to provide designers with directions by introducing functional structures and functional models. So that it can quickly dig out potential available resources, which solve the problem that patent knowledge cannot be directly transformed into functional knowledge and applied to product agile innovation design.

More than 90% of the development of new products in the manufacturing industry is based on the original product as reference object for innovation and improvement [2]. The TRIZ function model provides a conceptual description of a product or process [22], [25], [34]. It forms a conceptual model of the technology system by depicting elements and their relations [17]. Therefore, it is a good research direction to study how to satisfy the agile innovative design of products through the functional structure and functional model of existing knowledge. Liu et al. [10] use the functional structure model of the product to quantitatively compare the similarity between the function (source design) of previous successful cases and the function (target design) of the target product using the method of analogy design. Then he combines the TRIZ theory to get a conceptual innovation plan for the original understanding of product function. Stone [20], [21] quantitatively compared the similarity between functional structures through the functional similarity matrix. This method assisted in establishing the functional model of the new product. The above research uses the functional structure and functional model of similar products to meet the agile and innovative design of new product. However, there is also an obstacle to the establishment of new product functional model and functional structure, that is, a reasonable source of analogy is needed to overcome this obstacle. Computer-aided patent knowledge mining shows his advantages in the agile innovative design of products. Therefore, it seems to be a feasible method to transform the computer-aided mining patent text knowledge into functional structure and functional model for the agile and innovative design of products.

In summary, in order to meet the agile and innovative design of new products, this paper proposes a new design process model. First, the functional decomposition and functional structure of the new product are established based on the functional base. Second, a search strategy is construct in order to abstract the function into search keywords. It can be searched in the functional structure and functional model library extracted from the patent, which obtain the functional structure and functional model of similar product. Then, the patented products are quantitatively screened using the functional similarity matrix to obtain the most matching functional model. Finally, the TRIZ tool is used to establish the functional model of the new product and the final engineering design plan.

The contributions of this research are:

1. Proposed an agile innovation process model based on computer-aided patent knowledge mining and functional analogy. The computer-aided mining of patent knowledge into the form of functional models and functional structures, which enhances the practicality of using patent knowledge as an innovation resource.

2. The application of computer for data analysis reduces the amount of calculation of functional similarity, speeds up the search of similar product, and satisfies the agile and innovative design of new product.

2 RELATED THEORETICAL BASIS

Function analysis is a core part of the new product design stage, which includes abstract expression of function, functional standardization, functional classification and decomposition, etc. Combining computer-aided design and functional analysis, the theoretical basis is introduced below.

2.1 Functional Analysis

Functional analysis mainly includes the establishment process of functional structure and functional model, both of which are an important part of innovative design. Their main purpose is to decompose the total function of the product into small functional elements. Then, the decomposition result is to find the original understanding of each functional element. In the design process of new product, it is necessary to analyze the relationship between functional structure and functional model. According to the analysis results, the designer can establish suitable relationship to meet the important characteristics of nonlinearity, time-varying characteristics, coupling and openness in the complex product design process [3], [32].

Functional structure expresses the interaction relationship between the material flow, energy flow and signal flow as shown in figure 1. To establish functional structure of the product, the designer first determines the overall function of the product based on the interaction between the energy flow, material flow and signal flow. Then, the designer decomposes the total function of the product into sub-function until it is decomposed into the smallest functional element. Finally, the designer establishes an appropriate functional chain and functional tree according to the relationship between each functional element. The designer will revise and perfect the functional chain to obtain the product functional structure [22].

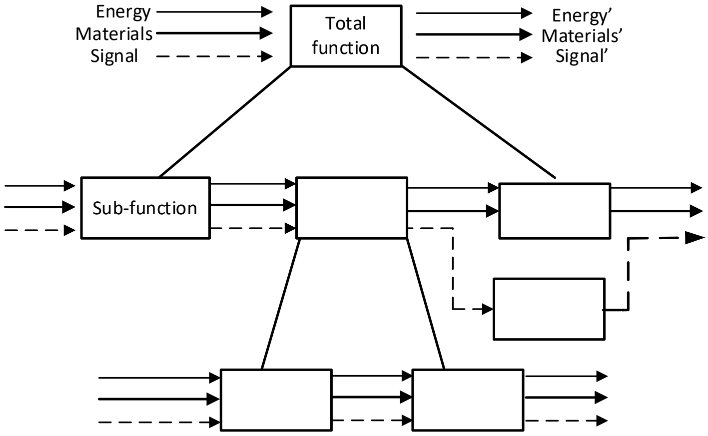

Figure 1: Product functional structure construction model diagram.

Functional model expresses interaction and attributes among the product, system and super-system [31]. The construction process of functional model is as follows: starting from the overall function, the system is decomposed into sub-system. The sub-system is decomposed until the representative components are found. Then, each element is connected to express the interaction. Different effect is represented by different lines, such as harmful effect, insufficient effect, etc. Finally, component, product and super-system are connected to establish a functional model, as shown in figure 2. Since it is an analysis of the interaction between components, functional model is mainly an improvement of existing products or systems.

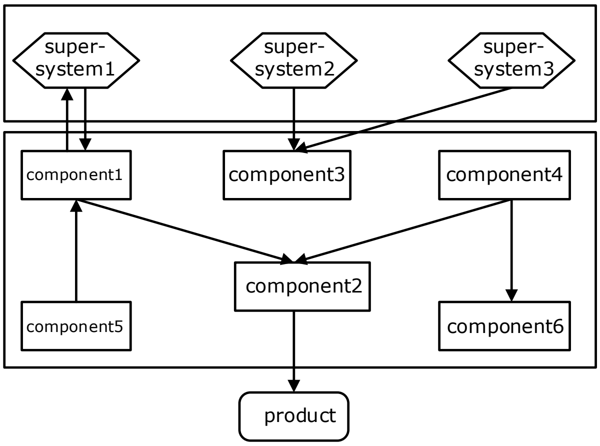

Figure 2: Product functional model construction model diagram.

2.2 Standardized Design Language: Functional Basis

The concept of functional basis was first proposed by Stone [21]. It is a universal language to build functional structure. It is mainly composed of functional set and flow set. In the functional basis, function is mainly represented by verb, which is divided into class function and basic function. The class function is mainly divided into eight categories, each of which can be expanded into many basic functions. The third column is the expanded stream function, which is only effective when it is used with a specific stream. The specific functional classification set is shown in table 1.

Class	*Basic*	*Flow restricted*	*Synonyms*
Branch	Separate		Switch, Divide, Release, Detach, Disconnect, Disassemble, Subtract
		Remove	Cut, Polish, Sand, Drill, Lathe
	Refine		Purify, Strain, Filter, Percolate, Clear
	Distribute		Diverge, Scatter, Disperse, Diffuse, Empty, Absorb, Dampen, Dispel, Resist, Dissipate
Channel	Import		Input, Receive, Allow, Form, Entrance, Capture
	Export		Discharge, Eject, Dispose, Remove
	Transfer	Transport	Lift, Move
		Transmit	Conduct, Convey
	Guide		Direct, Straighten, Steer
		Translate	
		Rotate	Turn, Spin
		Allow DOF	Constrain, Unlock
Connect	Couple		Join, Assemble, Attach
	Mix		Combine, Blend, Add, Pack, Coalesce
Control Magnitude	Actuate		Start, Initiate
	Regulate		Control, Allow, Prevent, Enable/Disable, Limit, Interrupt, Valve
	Change		Increase, Decrease, Amplify, Reduce, Magnify, Normalize, Multiply, Scale, Rectify, Adjust
		Form	Compact, Crush, Shape, Compress, Pierce
		Condition	
Convert	Convert		Transform, Liquefy, Solidify, Evaporate, Condense, Integrate, Differentiate, Process
Provision	Store		Contain, Collect, Reserve, Capture
	Supply		Fill, Provide, Replenish, Expose
	Extract		
Signal	Sense		Perceive, Recognize, Discern, Check, Locate
	Indicate		Mark
	Display		
	Measure		Calculate
Support	Stop		Insulate, Protect, Prevent, Shield, Inhibit
	Stabilize		Steady
	Secure		Attach, Mount, Lock, Fasten, Hold

	Position	Orient Align, Locate

Table 1: The collection and classification table of functions in the function basis [15].

In the functional basis, the flow set is defined as the energy, material and information. Flow set is expressed by noun, and it is divided into several major categories: Class, Basic flow, Sub-basic flow and Complement. The class flow is divided into material, signal and energy. According to these categories, the flow continues to be divided into many sub-categories. Finally, it forms a normative design language. The specific flow set is shown in table 2.

Class	*Basic*	*Sub-basic*	*Complements*	
Material	Human		Hand, foot, head, etc.	
	Gas			
	Liquid			
	Solid			
Signal	Status	Auditory	Tone, Verbal	
		Olfactory		
		Tactile	Temperature, Pressure, Roughness	
		Taste		
		Visual	Position, Displacement	
	Control			
Class	Basic	Sub-basic	Bond graph based complement	
			Effort analogy	Flow analogy
Energy	Human		Force	Motion
	Acoustic		Pressure	Particle velocity
	Biological		Pressure	Volumetric flow
	Chemical		Affinity	Reaction rate
	Electrical		Electromotive force	Current
	Electromagnetic	Optical	Intensity	Velocity
		Solar	Intensity	Velocity
	Hydraulic		Pressure	Volumetric flow
	Magnetic		Magnetomotive force	Magnetic flux rate
	Mechanical	Rotational	Torque	Angular velocity
		Translational	Force	Linear velocity
		Vibrational	Amplitude	Frequency
	Pneumatic		Pressure	Mass flow
	Radioactive		Intensity	Decay rate
	Thermal		Temperature	Heat flow

Table 2: The collection and classification table among the functional bases.

The functional basis plays an important role in the functional analysis. Functional structure is standardized through functional basis, which is helpful to the establishment of database information. And it provides a new method for comparing the similarity between different functional structures.

3 FUNCTION ANALOGY PROCESS BASED ON COMPUTER-AIDED DESIGN

3.1 CAD-Based Functional Structure and Functional Model Library Establishment

This article uses MATLAB GUI for software development. The MATLAB GUI is a graphical user interface that can realize the design of man-machine software interface. It can be achieved by writing a callback function. There is the description of connection relationship between the components in the patent specification. In this article, the text information in the patent is segmented to obtain elements (nouns) and their connection relationships (verbs). These components are connected to get a functional model. According to the established functional model, the functional structure is also established. The functional structure and functional model are saved in the form of pictures. And they are stored through MATLAB GUI software. The functional structure and functional model of similar patents are stored in a library. When inputting a functional description (subject + predicate + object), the designer clicks OK to retrieve functional structure and function model of similar product. And computer-aided design software has a calling function. After new product has established functional structure and functional model, it can be called by clicking the Call button. Then, the developer selects functional structure and functional model of new product, and the file name is displayed in the filename. Finally, when the developer clicks the Add button, functional structure and functional model of new product will be saved in the library. This software achieves the expansion of database. And the CAD modeling software realizes the extraction of information in patents. This modeling software improves the design speed of new product and provides convenience for designer.

New product development or introduction of new system function is an important component of product innovation design. In the development of new product, a few products are brand-new design, and most of them reuse existing components or modify past parts and components. The product design has achieved product innovation by learning from similar products. The computer-aided innovation software will provide a lot of help. The patent has the following connection relationships, for example, element 1 is connected to element 3 through element 2. The functional structure and functional model from the patent are put into the database to improve design efficiency. First, the functional description is performed. Then, the simplest form of subject + predicate + object in the functional description is extracted. Then the designer can identify similar products based on the similarity between the functional structures after the standardization of the functional basis. This function can meet the increase and expansion of the database, and it can provide more design solutions for the design of new product in the future. For example, if inputting a workpiece sorting device, the software will automatically output a knowledge base of multiple types of workpiece sorting products as shown in figure 3.

3.2 Similar Product Function Analogy Process

To find similar products easily, the designer uses the method of functional similarity matrix [20]. Through the quantitative comparison between the functions of new product and the functions of the existing product, the product with the highest similarity is selected to assist in the subsequent product design. The standardized formula calculation is shown in (1).

$$N_{ij} = \phi_{ij}\left(\frac{\overline{\eta}}{\eta_j}\right)\left(\frac{\mu_j}{\overline{\overline{\mu}}}\right) \tag{1}$$

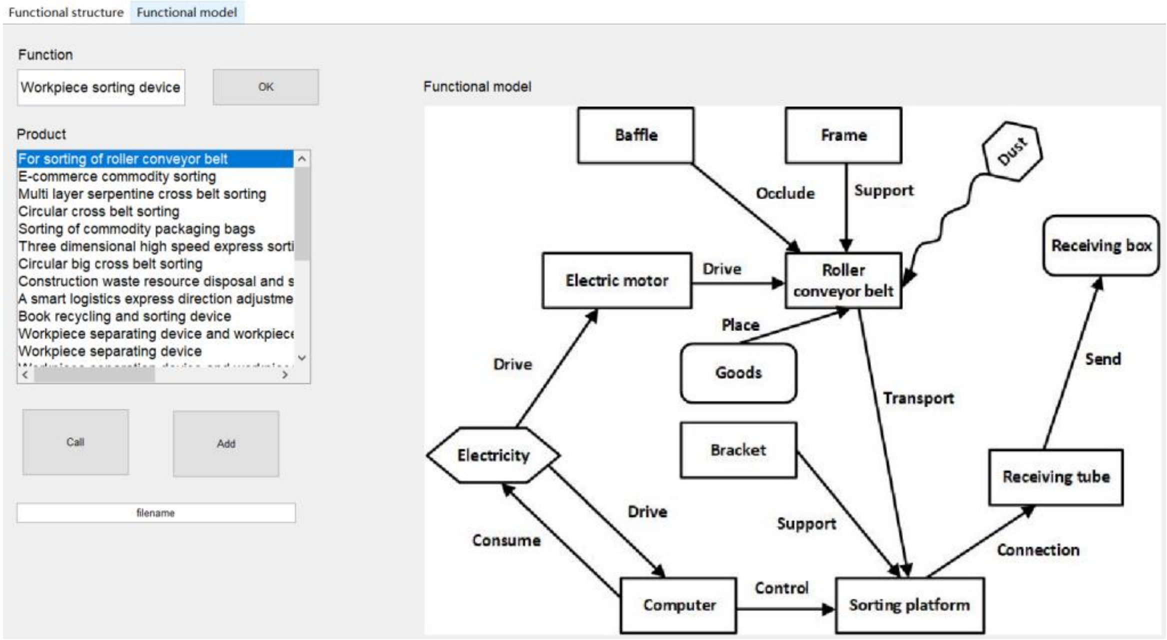

Figure 3: The functional model of software for workpiece sorting device.

N_{ij} represents the i-th function of the j-th product in the matrix N , ϕ_{ij} represents the i-th function of the j-th product in the matrix ϕ , and $\bar{\eta}$ represents the average value of the elements ϕ_{ij} in the matrix ϕ , and the calculation formula is as shown in (2). η_j represents the functional weight sum of the j-th product, and the calculation formula is as shown in (3). μ_j represents the sum of the weight values of the elements in the canonical matrix H , as shown in (4). $\bar{\mu}$ represents the average value of all elements in the canonical matrix H , as shown in (5).

$$\bar{\eta} = \frac{1}{n}\sum_{i=1}^{m}\cdot\sum_{i=1}^{n}\phi_{ij} \tag{2}$$

$$\eta_j = \sum_{i=1}^{m}\phi_{ij} \tag{3}$$

$$\mu_j = \sum_{i=1}^{m}H(\phi_{ij}) \tag{4}$$

$$\bar{\mu} = \frac{1}{n}\sum_{i=1}^{m}\cdot\sum_{i=1}^{n}H(\phi_{ij}) \tag{5}$$

The normalized matrix H is mainly to eliminate the subjectivity of customer demand and reduce the complexity of functions. Hij represents the i-th function of the j-th product. When the required function exists in the product, it is assigned a value of 1, otherwise, it is 0, as shown in (6).

$$Hij = \begin{cases} 1 & \text{When function in the jth product} \quad i \neq 0 \\ 0 & \text{When function in the jth product} \quad i = 0 \end{cases} \tag{6}$$

According to the calculation formula of the functional similarity matrix, the designer uses MATLAB tool to process the data, and the interface of the data processing is shown in figure 4.

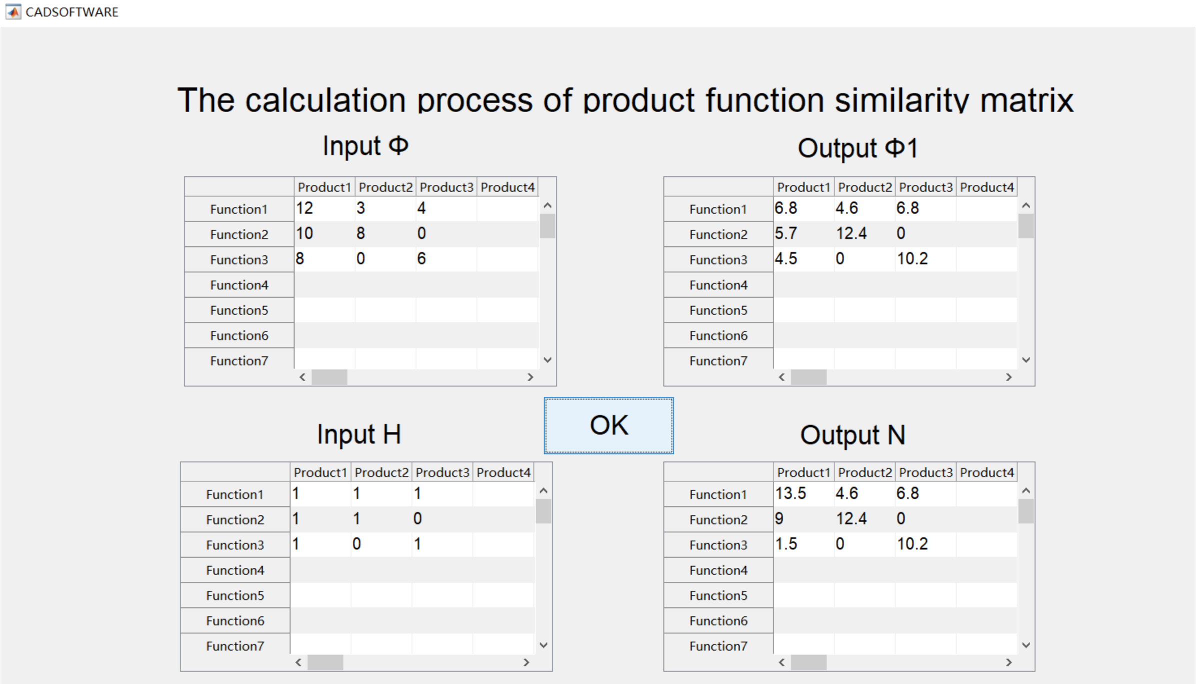

Figure 4: Software analysis interface of function similarity matrix.

When the function similarity matrix value and the normalized matrix value are input into the software, the software automatically outputs the final results. This software improves the calculation accuracy and design efficiency. Then, according to the functional similarity matrix N, the patented product with the highest functional similarity is calculated. Finally, each functional model is analyzed to assist establishment of functional model according to functional model of similar products.

4 CAD-BASED AGILE INNOVATION DESIGN PROCESS MODEL

The functional model is an important part of product design. How to design the functional model of the system will play an important role in the development of new products. The following is an analysis of the agile design process.

4.1 Preliminary Demand Analysis

The acquisition of functional demand has always been a difficult point in the analysis of system demand [14]. At the same time, functional demand is the front-end design for designing new products, and it is also an important step in product innovation. Complex product scheme design demand describes the static attribute information of customer demand. Characteristic demand is related to the physical properties and performance of the product, such as weight, quality, materials, operability, etc.; Structural demand is related to the structure of product parts and product shape characteristics; Functional demand is related to the functional attributes of the product; Environmental demand refers to the working environment and working condition; Relational demand refers to the existence of constraints or dependencies between demand characteristics, which generally include configuration relationships, comparison relationships, logical relationships, etc. [5]. This paper analyzes the customer demand to get the final feasible demand plan.

4.2 Construction Process of New Product Function Model

Functional structure expresses the relationship between the material flow, energy flow and signal flow of the system. Through functional decomposition, the total function is decomposed into sub-functions. Then, each sub-function is decomposed layer by layer until it becomes non-decomposable functional elements. Combination of these functional elements constitutes functional structure of the product or system. The designer standardizes the functional structure of new product based on the functional basis. Then, the designer compares the functional structure of similar products with the functional structure of new product. Then the designer combines the available resource analysis tool in TRIZ to assist in establishing a preliminary functional model of new product. Finally, the redundant functional part in the functional model is analyzed and the redundant part is trimmed [28], [29] to obtain the trimmed functional model.

The functional element uses the form of "verb + noun" (Verb + Noun) to express the action (Act) and the target (Target). The original understanding of functional element is expressed in the form of "execution object + action + acted object". For example, "Hit the nail", which represents the acting object and the acting object in the form of verb + noun. By solving its execution object, such as a hammer, then the hammer hitting the nail represents the original understanding. The role and the affected object can be expressed by equation (7).

$$V + N \rightarrow A + T \tag{7}$$

In formula (7), "V+N" represents a functional element. "A" represents an effect, and "T" represents an object to be acted upon. The execution object (EO) can be obtained by obtaining the original understanding of function element. Therefore, a function information contains a formula of "execution object + action + action object", as shown in equation (8).

$$f = \{EO, A, T\} \tag{8}$$

The designer combines the analysis of available resources to get the original understanding of other functional elements. Based on the original understanding of other functional elements, new components are added into functional model after preliminary trimming. And the conflict tool in TRIZ conduct a systematic analysis. Finally, the final functional model of new product is obtained. The graphical expression of establishment process is shown in figure 5.

4.3 Agile Process Model Building Process

Figure 6 is an agile innovation process model based on computer-aided patent knowledge mining and functional analogy. The steps are as follows.

1) First, demand analysis is conducted.
2) Second, according to the results of demand analysis, the designer determines the overall function and performs functional decomposition.
3) Third, according to the results of functional decomposition, the designer establishes the functional structure of new product.
4) Fourth, according to the total function analysis, the function model and function structure of similar products are found through computer-aided innovation software.
5) Fifth, the designer makes functional analogy through the functional similarity matrix to find similar products.
6) Sixth, the designer combines resource analysis tool to obtain a preliminary functional model. According to the conflict analysis tool in TRIZ, the inadequate and harmful effects in the system are eliminated.
7) Gray-level correlation method and analytic hierarchy process evaluate the plan.

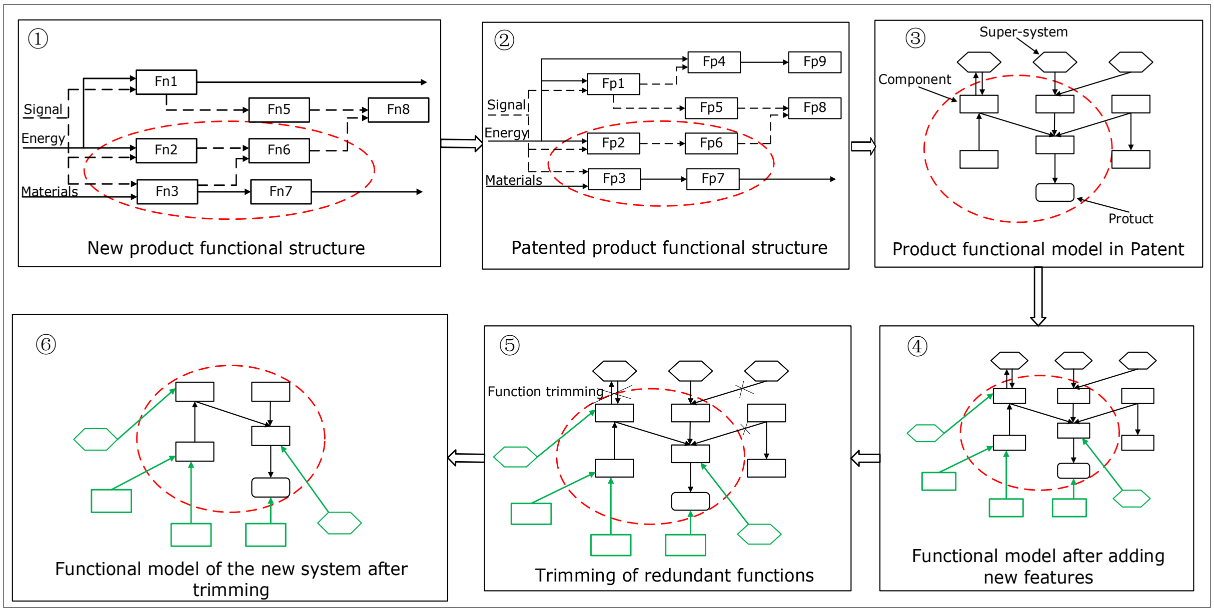

Figure 5: New product function model construction process diagram.

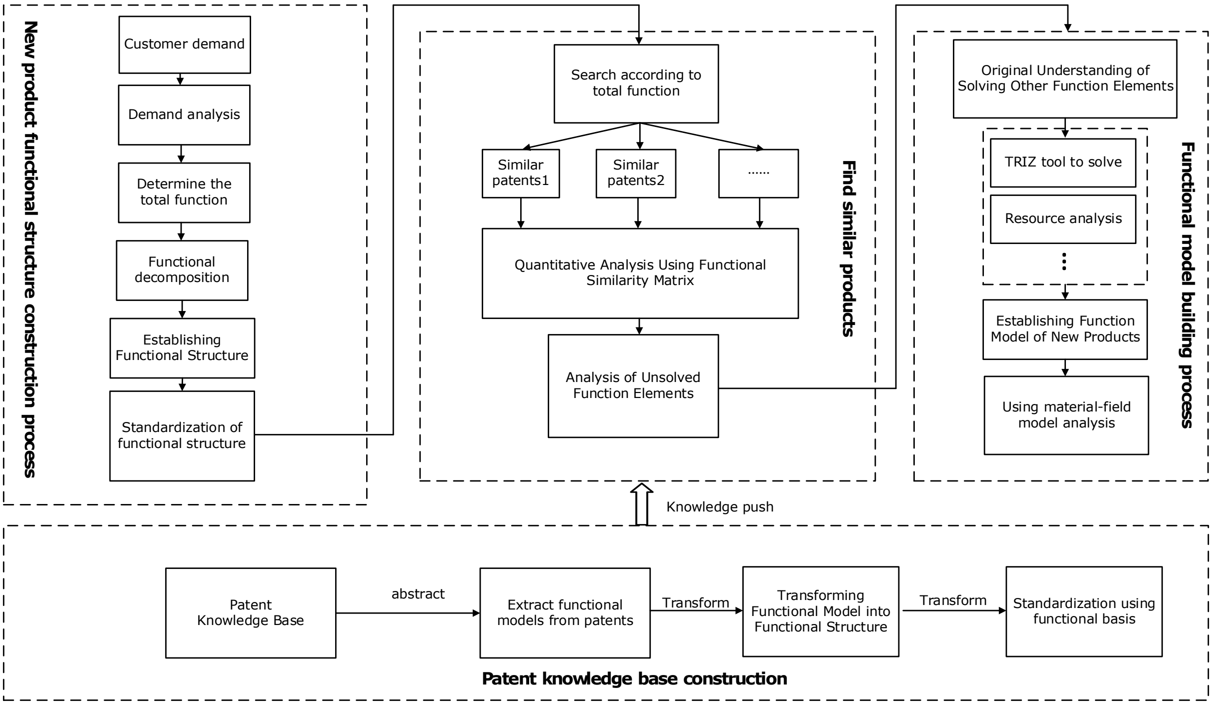

Figure 6: Agile innovation process model based on computer-aided patent knowledge mining and functional analogy.

5 PROJECT CASE VERIFICATION

5.1 Scheme Design of Natural Wind Dust Removal System

As a kind of clean energy, solar energy is replacing fossil energy to become a new trend of social development, and it has a good development prospect. With the rapid development of solar power generation technology, the widespread application of solar panels has provided convenience for solving the problems of energy shortage and sustainable development. However, because the number of solar panels is increasing, it has brought many problems to the later operation and maintenance of solar panels. For example, solar panels are generally used outside. After a long period of use, the surface area is covered with dust that has a serious impact on conversion efficiency. Therefore, the regular cleaning of solar panels is particularly important. In some studies at home and abroad, manual wiping, water gun cleaning and waterless robot cleaning are the most commonly cleaning methods. However, these cleaning methods have the problems of high resource consumption, incomplete cleaning and low cleaning efficiency. However, they cannot meet the cleaning demand. Aiming at the problem of dust cleaning on the surface of solar panels, this paper designs a natural wind dust removal system. The following is the specific steps of system production.

Step1: The designer conducts demand analysis of the system. Abundant natural resources is used to reduce losses and environmental pollution, and the cleaning efficiency of solar panels is higher. Through investigation, it is found that dust removal is not affected by day and night. The dust removal system should have a high degree of automation, low complexity and stable work to meet basic manufacturing demand. Also, the system need have monitoring equipment to meet basic operation and maintenance demand.

Step2: According to the results of comprehensive demand analysis, the overall function is to remove dust from solar panels, and then the designer performs functional decomposition to establish a preliminary functional decomposition model as shown in figure 7. Then, based on the results of functional decomposition, the designer establishes the preliminary functional structure of the solar dust removal system as shown in figure 8.

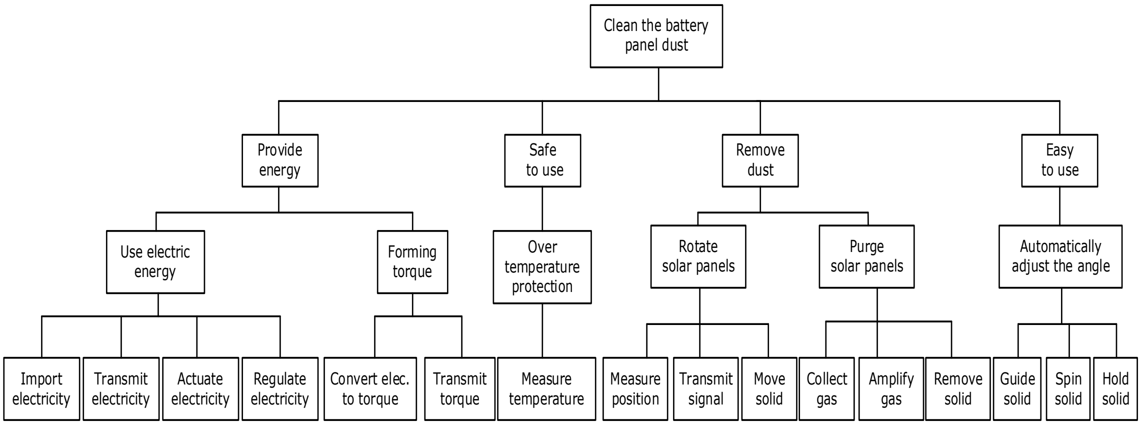

Figure 7: Functional decomposition diagram of solar panel dust removal system.

Step3: The designer found similar functional structures and functional models of the solar dust removal system from the patent database. The search results of the solar dust removal system patent database are shown in figure 9 and figure 10.

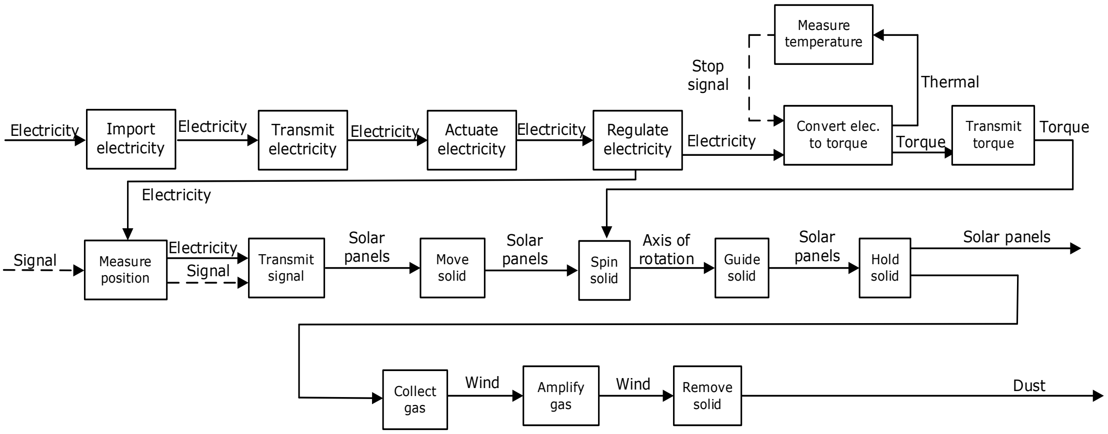

Figure 8: Functional structure diagram of solar panel dust removal system.

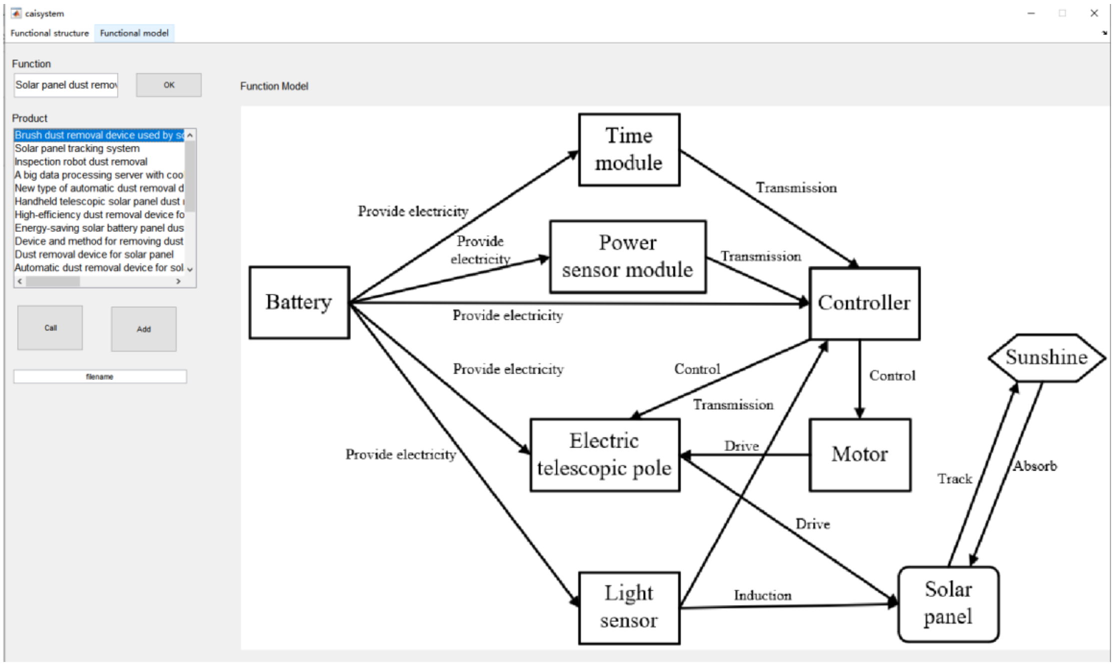

Figure 9: Solar dust removal system demand-function analysis function model.

Step4: According to the search results, the designer establishes a functional similarity matrix. The designer obtains the weight value of each function according to the demand level 1~5, as shown in table 3.

According to the weight value between demand and function, the designer accumulates the function weight value to obtain the total function weight value. The specific function weight value is shown in table 4.

In the same way, according to the search results of the software library, the designer finds similar products and analyzes the function weight value to obtain the function weight value of similar products, as shown in table 5.

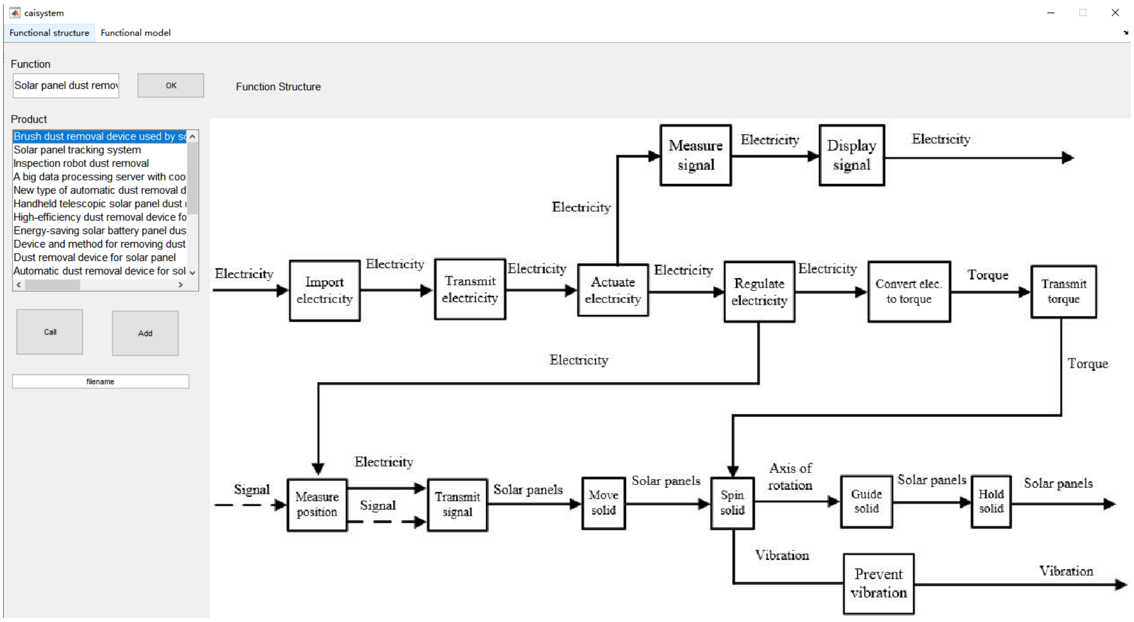

Figure 10: Solar dust removal system demand-function analysis function structure.

Customer demand	*Customer demand weight value*	*Assigned flow*	*Related sub-functions*
good dust removal effect	5	solar panels dust	measure position、transmit signal、move solid、collect gas、amplify gas、remove solid
use clean energy	5	wind	collect gas、amplify gas、remove solid
easy to operate	4	solar panel wind dust	collect gas、amplify gas、remove solid、move solid、guide solid、spin solid、hold solid
high security	4	electricity temperature dust	import electricity、transmit electricity、actuate electricity、regulate electricity、measure temperature、measure position、amplify gas、remove solid
stable job	4	torque	convert elec. to torque、

		temperature solar panel	transmit torque、transmit signal、measure position、measure temperature、move solid、guide solid、spin solid、hold solid
low energy consumption	3	electricity wind	import electricity、transmit electricity、actuate electricity、regulate electricity、transmit signal、measure position、collect gas、amplify gas、remove solid
cheap cost	3	wind solar panel	collect gas、amplify gas、remove solid、move solid、guide solid、spin solid、hold solid
low noise	3	sound energy solar panel	move solid、guide solid、spin solid、hold solid、measure position、transmit signal
simple structure	2	solar panel wind	move solid、collect gas、amplify gas、remove solid
small size	2	wind dust	amplify gas、remove solid
easy to maintain	2	solar panel	guide solid、spin solid、hold solid

Table 3: Solar panel dust removal system demand-function analysis.

Related sub-functions	*Weight value*	*Weight value sum*
remove solid	5，5，4，4，3，3，2，2	28
amplify gas	5，5，4，4，3，3，2	26
collect gas	5，5，4，3，3，2，2	24
move solid	5，4，4，3，3，2	21
measure position	5，4，4，3	16
guide solid	4，4，3，3，2	16
spin solid	4，4，3，3，2	16

transmit signal	5，4，3，3	15
hold solid	4，4，3，2，2	15
measure temperature	4，4	8
import electricity	4，3	7
transmit electricity	4，3	7
actuate electricity	4，3	7
regulate electricity	4，3	7
convert elec. to torque	4	4
transmit torque	4	4

Table 4: The function weight value of solar panel dust removal system.

Related sub-functions	*Solar panel dust removal system*	*A solar panel tracking system*	*Solar dust removal device CN206422746U*	*Solar panel dust removal device CN204746947U*
remove solid	28	0	20	22
amplify gas	26	0	0	0
collect gas	24	0	0	0
move solid	21	18	15	8
measure position	16	14	10	0
guide solid	16	14	12	4
spin solid	16	14	0	0
transmit signal	15	13	10	0
hold solid	15	8	6	0
measure temperature	8	0	0	0
import electricity	7	5	6	0
transmit electricity	7	5	6	0
actuate electricity	7	5	6	0
regulate electricity	7	5	6	0
convert elec. to torque	4	3	0	0

transmit torque	4	3	0	0

Table 5: Function weight value of similar products.

The function weight value is input into the MATLAB software for data processing, and the designer obtains the function weight value of each product as shown in figure 11. The results of CAD software data processing are shown in table 6.

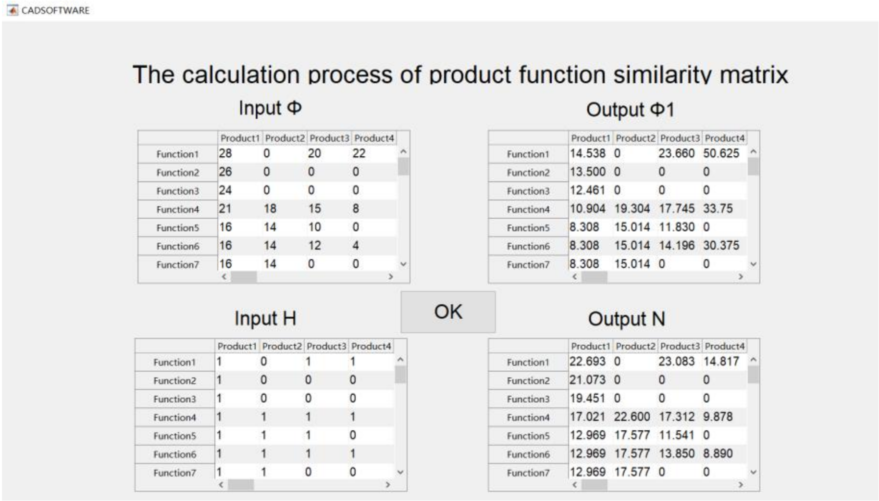

Figure 11: Functional similarity matrix software processing results

Related sub-functions	*Solar panel dust removal system*	*The solar panel tracking system*	*Solar dust removal device CN206422746U*	*Solar panel dust removal device CN204746947U*
remove solid	22.693	0	23.083	14.817
amplify gas	21.073	0	0	0
collect gas	19.451	0	0	0
move solid	17.021	22.600	17.312	9.878
measure position	12.969	17.577	11.541	0
guide solid	12.969	17.577	13.850	8.890
spin solid	12.969	17.577	0	0
transmit signal	12.157	16.322	11.541	0
hold solid	12.157	10.044	6.925	0
measure temperature	6.484	0	0	0
import electricity	5.674	6.277	6.925	0
transmit	5.674	6.277	6.925	0

electricity				
actuate electricity	5.674	6.277	6.925	0
regulate electricity	5.674	6.277	6.925	0
convert elec. to torque	3.242	3.766	0	0
transmit torque	3.242	3.766	0	0

Table 6: Functional similarity matrix of the solar dust removal system.

In table 6, the function weight value of each function is calculated by the demand-function level. Then, the functional similarity matrix is used for quantitative calculation of similar products. Finally, the weight value of each function is analyzed through computer. Each customer demand is given a weight value. According to the degree of importance, for example, the obvious dust removal effect and clean resources have the high importance, so the demand weight value is assigned to 5. The demand of simple structure and small volume have less influence on the design system, so the demand weight value is assigned to 2. If a function affects a specific customer demand, the demand score is assigned to the function. If customer demand is related to multiple functions, each function will have multiple points assigned by customer demand. Then, each score is added to get the relative importance score of the product function. After judging customer needs, the total score of functional importance is obtained. After the total score of the product function is obtained, a normalized matrix is established. Then, the final weight value of each function is obtained through the function similarity calculation formula. For example, the flow set corresponding to the removal of solids is dust. Search for all functions related to dust in the functional structure to establish a connection between customer need and function. There is no function of removing solids in the solar panel tracking system, so the corresponding function weight value is 0. In the same way, according to each function value corresponding to each customer demand, the function weight value is accumulated to obtain the size of the function weight value.

According to the quantitative calculation results of the similarity matrix, the solar tracking system has a high degree of similarity. However, it does not have the function of removing solids; A solar panel dust removal device (patent number CN206422746U) can meet the basic dust removal function. However, the dust removal tool uses is a motor-driven roller to achieve the dust removal function. Through the analysis of similar products, the designer obtains the execution objects of each functional element, as shown in table 7.

i	*Vi*	*Ni*	*Ai*	*Ti*	*EO*$_i$
1	remove	solid	remove	dust	Brushes/rollers
2	amplify	gas	amplify	wind	not find
3	collect	gas	collect	wind	not find
4	move	solid	move	solar panels	rotating rod
5	measure	position	measure	solar panels	position sensor
6	guide	solid	guide	solar panels	rotating rod
7	spin	solid	spin	solar panels	rotating rod
8	transmit	signal	transmit	wind signal	microcontroller

9	hold	solid	hold	solar panels	bracket
10	measure	temperature	measure	temperature	temperature sensor
11	import	electricity	import	electricity	accumulator
12	transmit	electricity	transmit	electricity	accumulator
13	actuate	electricity	actuate	electricity	switch
14	regulate	electricity	regulate	electricity	switch
15	convert	electricity	convert	electricity	motor
16	transmit	torque	transmit	rotating rod	motor

Table 7: The solution results of the solar panel execution object.

Step5: Through searching similar products in the patent database, the designer can get the original understanding of solar panel dust removal system. Then, the designer uses the resource analysis in TRIZ to analyze the available resources. The designer analyzes material resources, energy resources, time resources, space resources and information resources to improve these functions of the system. The results of the available resource analysis are shown in table 8.

Material resources	*Energy resource*	*Time resource*	*Space resource*	*information resource*
solar panel	electricity	power generation time	space where the solar panels are located	panel size
wind direction adjustment device	mechanical energy	Time for the dust to accumulate		the wind direction in a certain area
wind power amplifier	thermal energy	microcontroller processing data time		Solar panel power generation
solar panel bracket	light energy	time to clean up the dust		
microcomputer	wind energy			
motor				

Table 8: The results of the available resource analysis.

According to the analysis of available resources, wind energy is a clean resource. Wind energy can replace the original brushes to clean solar panels. This method not only saves energy but also makes full use of the advantages of wind energy. However, the intensity of wind is uncertain, and the device needs to be able to achieve the dust removal effect even when the wind is small. Therefore, the device needs to design an air amplification system. And the system needs to monitor the wind intensity and direction in real-time. Based on the above theoretical analysis, the designer designs a functional model of the solar dust removal system, as shown in figure 12.

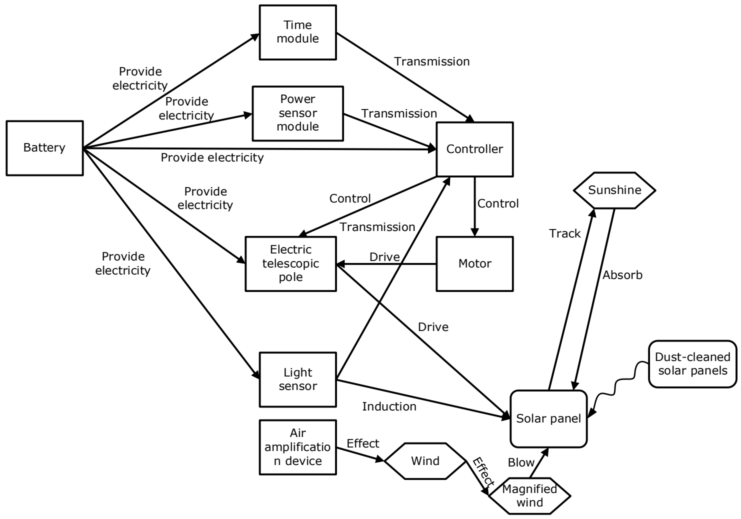

Figure 12: Functional model of natural wind dust removal system.

Step6: The harmful effect tool in TRIZ analyzes the functional model of solar panel natural wind dust removal system. Dust-cleaned solar panels are harmful. It may fall into the dust when the next solar panel is cleaned. According to the standard solution in the TRIZ theory, the harmful effect uses the 1.2 type standard solution to eliminate. And the designer gets the standard solution No.10(1.2.2). In a system, the designer improves the support structure of solar panels to improve its performance indicators. According to standard solution No.10 (1.2.2), the solar panel after dust removal rotates at a certain angle to prevent dust from falling on the clean solar panel again. The substance-field model is shown in figure 13.

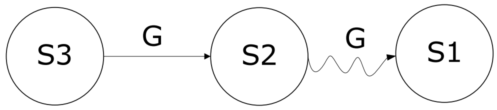

Figure 13: Substance-field model of the solar dust removal system.

Step7: LABVIEW is a graphical programming language that uses icons instead of text lines to create applications. It is also an instrument-oriented development environment. Using LABVIEW not only collects and analyzes data, but also can display, store and other operations. This tool greatly shortens the development cycle of the program and significantly improves the development efficiency of users. In order to meet the demand of operation and maintenance, monitoring interface of wind speed and wind direction is compiled through LABVIEW software, as shown in figure 14. The lower computer of the solar dust removal system collects data of wind speed, wind direction, and solar panel voltage. The data is transmitted to the upper computer through serial communication. The upper computer processes, saves and displays the data. It is mainly composed of two parts: the serial port parameter setting part and the parameter display part. The serial port parameter setting includes serial port number selection, baud rate setting, inspection mode selection, data bit and stop bit setting. These parameters are set in the rear panel program. This method can avoid the trouble that resetting the monitoring interface when you log in every time. If necessary, the designer can modify it on the rear panel. The parameter display is composed of wind speed, wind direction and solar panel voltage. In this way, the wind speed and wind direction can be monitored in real time.

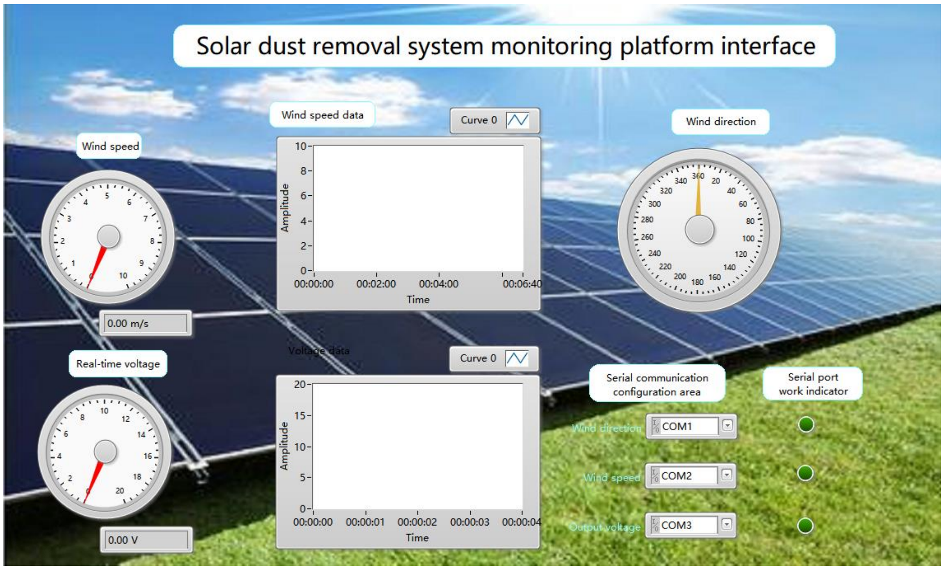

Figure 14: Solar dust removal system monitoring platform interface.

Finally, the designer finds the principle of the tapered nozzle based on the scientific effect. The air amplification device is designed with a tapered nozzle as a model, which can effectively increase the air velocity and achieve the effect of air amplification. The three-dimensional simulation model of the air amplifying device and physical diagram is shown in figure 15.

Figure 15: Left: Air amplification device of the solar dust removal system; Right: Physical image of the solar dust removal system.

5.2 Evaluating the Design Solution

For the evaluation of the design plan, this article uses an evaluation system that combines the grey evaluation method [26] and the analytic hierarchy process (AHP) method [33]. This article compares the traditional waterless robot cleaning device with the solar panel natural wind dust removal device.

1) Establishing an evaluation indicator system

According to the reference [7], the three comprehensive indicators of use performance, economic performance and green performance are subdivided, and the final evaluation indicators are established as shown in the table 9.

Target Layer	Comprehensive Indicator Layer (Weight value)	Project Indicator Layer (Weight Value)
characteristics of mechanism	U1 use performance（0.72）	U11 reliability（0.60）
		U12 operability（0.20）
		U13 maintainability（0.20）
	U2 economic performance（0.09）	U21 cost of development（0.54）
		U22 production cost（0.12）
		U23 maintenance cost（0.34）
	U3 green performance (0.19)	U31 environmental protection（0.11）
		U32 vibration and noise（0.63）
		U33 energy-conservation（0.26）

Table 9: The final evaluation indicators.

2) Determining the evaluation rule and weight

First, the evaluation rules of the evaluation indicators are formulated according to their difference and size, as shown in table 10.

Description	Very Good	Good	Moderate	Not Very Good	Not Good	Very Bad
Score	9 – 10	7 – 8	5 – 6	3 – 4	1 – 2	0 – 1

Table 10: Score evaluation.

In the proposed method, the analytic hierarchy process (AHP) is used to determine the weights, and the relative importance of each factor is measured by introducing an appropriate measurement scale. Thus, a judgment matrix (denoted by A, where element x_{ij} in A represents the relative importance of e_i and e_j, and $x_{ji} = 1/x_{ij}$) is constructed, and its consistency is evaluated. Through an inspection of the matrix, its eigenvector is calculated as the corresponding weight value. The evaluation indicators are divided into five grades: equally important, slightly important, important, quite important and extremely important. They correspond to scores of 1, 3, 5, 7 and 9, respectively, while 2, 4, 6 and 8 are the corresponding intermediate grades [26].

The “summation method” is used to calculate the feature vectors [1] of the judgment matrix:

The original judgment matrix $X = (x_{ij})_{n \times k}$ is normalized according to columns, and X' is obtained:

$$x_{ij}' = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{9}$$

The vector ω' is calculated:

$$\omega_i' = \sum_{j}^{k} x_{ij}' \tag{10}$$

ω' is normalized to obtain the feature vectors:

$$\omega_i = \frac{\omega_i}{\sum_{i=1}^{n} \omega_i'} \tag{11}$$

The weight set of the comprehensive indicator layer is determined by the above method and is denoted by $\omega = \{\omega 1, \omega 2, \omega 3\}$, and the weight set of the project indicator layer is $\omega_i = \{\omega_{i1}, \omega_{i2}, \cdots, \omega_{ij}\}$. Due to space limitations, this paper presents the project indicator layer according to the above method and the judgment matrix of the first layer:

$$\begin{bmatrix} A & U_1 & U_2 & U_3 \\ U_1 & 1 & 5 & 7 \\ U_2 & 1/5 & 1 & 1/3 \\ U_3 & 1/7 & 3 & 1 \end{bmatrix}$$

The matrix passes the consistency test. Then, using Formulas (9) - (11), its feature vector can be obtained: $\omega = \{\omega 1, \omega 2, \omega 3\} = \{0.72, 0.09, 0.19\}$.

Similarly, the second judgment matrix $A1$, $A2$ and $A3$ can be obtained by using the above method:

$$\begin{bmatrix} A_1 & U_{11} & U_{12} & U_{13} \\ U_{11} & 1 & 3 & 3 \\ U_{12} & 1/3 & 1 & 1 \\ U_{13} & 1/3 & 1 & 1 \end{bmatrix}$$

$$\begin{bmatrix} A_2 & U_{21} & U_{22} & U_{23} \\ U_{21} & 1 & 3 & 3 \\ U_{22} & 1/3 & 1 & 1/5 \\ U_{23} & 1/3 & 5 & 1 \end{bmatrix}$$

$$\begin{bmatrix} A_3 & U_{31} & U_{32} & U_{33} \\ U_{31} & 1 & 1/3 & 1/5 \\ U_{32} & 3 & 1 & 1/3 \\ U_{33} & 5 & 3 & 1 \end{bmatrix}$$

The matrix above passes the consistency test. Formulas (7) - (9) are used to obtain its feature vector as follows:

$$\omega_1 = \{0.60, 0.20, 0.20\}$$
$$\omega_2 = \{0.54, 0.12, 0.34\}$$
$$\omega_3 = \{0.11, 0.26, 0.63\}$$

3 TRIZ field experts and 2 engineering technicians from Hebei University of Technology were invited to score each indicator in the project indicator layer (see the appendix for detailed scoring results). Finally, the scoring result is brought into formula (12).

$$W = \frac{\sum_{1}^{m}(\sum_{i=1}^{n} A_i W_i)}{m} \tag{12}$$

In the formula, m refers to the number of experts, n is the number of evaluation indices, A_i is the score of evaluation index i, W_i is the weight of evaluation index i and W is the total score.

The final results are shown in table 11.

Comprehensive Evaluation Indicator	Traditional waterless robot cleaning device	Solar panel natural wind dust removal device
use performance	6.44	6.52
economic performance	4.58	5.58
green performance	6.27	6.37
The final score	6.24	6.41

Table 11: Final evaluation results of system.

According to the final evaluation results shown in Table 11, it can be seen that the mechanical performance of the solar panel natural wind dust removal system has been significantly improved.

5.3 Dust Removal Effect Verification

The solar panel dust removal system is placed outside. The designer measures the output voltage of the solar panel before and after dust removal. Firstly, the designer measures the output voltage of a clean solar panel under a certain light condition (initial value V0). Then, the designer evenly places a certain amount of dust on the solar panel. In addition, the designer evenly places a certain amount of dust on the solar panel and measures the output voltage of the solar panel. Moreover, the dust removal efficiency is calculated by the formula n=[(V2-V0) - (V1-V0)]/V0. The designer abides by the principle of controlled variables. The designer changes the lighting conditions but keeps the amount of dust and wind speed constant. Under the condition that the battery board is kept horizontal, the designer performs multiple measurements according to the above steps, and the experimental data is shown in table 12.

Serial number	Initial voltage (V0)	Voltage before dust removal(V1)	Voltage after dust removal (V2)	Dust removal efficiency (n)
1	17.31	15.62	16.74	0.064702
2	16.76	15.03	16.15	0.066826
3	16.01	14.31	15.33	0.063710

4	15.04	13.55	14.38	0.055186
5	16.67	14.88	15.85	0.058188
6	16.83	15.13	16.12	0.058824
7	15.60	14.21	14.96	0.048077
8	15.91	14.40	15.21	0.050911
9	17.08	15.55	16.42	0.050937
10	17.64	16.01	16.99	0.055556
11	16.26	14.57	15.54	0.059656
12	16.06	14.74	15.49	0.048568
13	15.83	14.57	15.25	0.042956
14	15.44	14.43	15.01	0.037565
15	17.11	15.10	16.27	0.068381
16	17.67	15.95	16.96	0.057159
17	17.43	15.81	16.81	0.057372
18	17.35	15.76	16.75	0.057061
19	17.20	15.61	16.62	0.058721
20	17.00	15.41	16.39	0.057647

Table 12: Comparison of dust removal efficiency.

In order to show the efficiency of dust removal more clearly, the table data is expressed in the form of graph as shown in figure 16.

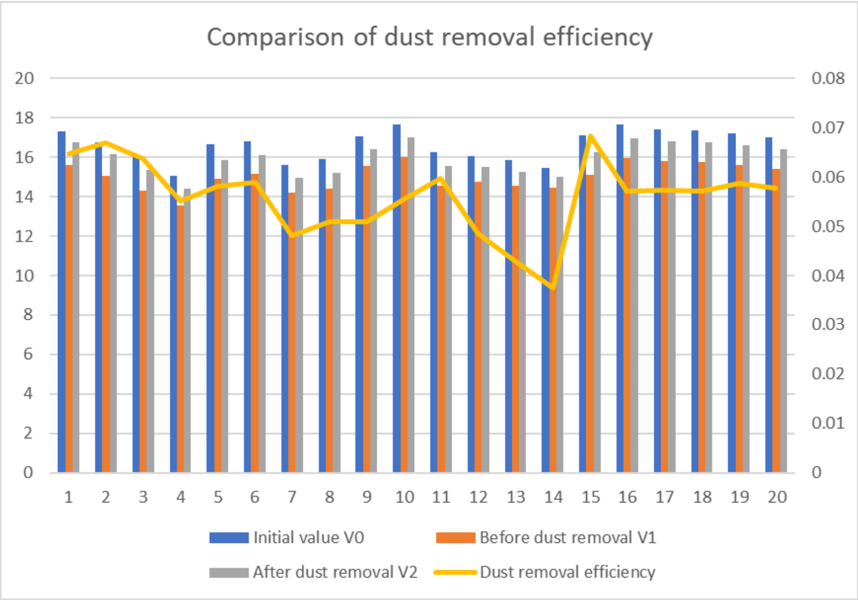

Figure 16: Comparison of dust removal efficiency.

In figure 15, the voltage value after dust removal is larger than the voltage value measured without dust removal, and it is closer to the initial value. The change of the initial voltage before and after dust removal by the LABVIEW host computer represents the level of dust removal efficiency. The results of 20 sets of experiments show that the voltage changes before and after dust removal are obvious. Although the data of the 14th group increased by about 3%, the data of other groups basically remains above 5%. The dust removal effect has been significantly improved. It proves the scientificity and feasibility of the product designed by this design method.

6 CONCLUSION

Facing the rapid development of today’s society, the functional requirements of products are constantly improving with people's demand standards. The design method of this research focuses on meeting the needs of rapidity and agility in product design. Firstly, computer aided technology is mainly used to transform a large amount of text information in patents into functional structures and functional models. Secondly, in order to find out similar functional structures and functional models in the patent, the functional similarity matrix is used with computer-based data analysis. Finally, a new product is designed. The new product solar panel dust removal system designed by this method has been verified by experiments that the dust removal effect is significant.

Compared with the original traditional design method, the design method proposed in this paper introduces patent knowledge as the knowledge source to inspire the designer in the design process, so that the designer can quickly identify similar products. And with the help of the computer to process the data of the functional similarity matrix, the speed of the design is accelerated and the agility and innovative design of the product is satisfied.

Despite great efforts for contributing new design methods, the limitations of this study are also obvious. First of all, the establishment of a graphical function model of patent knowledge is an arduous but indispensable step in this method and also the method of mining patent knowledge and applying it to the agile innovative design of products. However, the functional models and functional structures of the patents mining in this research can only model part of the patent knowledge and store the functional models in the software library. Additionally, in order to avoid patent infringement, designers must consider the claims in the patent when selecting similar patents. As the final solution of product agile design, designers also need to have enough design knowledge and experience. Finally, the design method proposed in this study may have a little subjective judgment in some steps, which may affect the generality of the design method.

In order to improve the proposed method and overcome the above-mentioned limitations, four key research directions can be explored in the future. First, more attempts will be made to dig out knowledge in different fields, such as biological knowledge, which will produce more effective and creative solutions. In addition, by placing the functional model and functional structure of new products, the continuous development of the database of patent knowledge will enhance its ability to assist with more different design issues. Moreover, it will be necessary to develop an intelligent retrieval module to cope with the continual expansion of the patent knowledge base. Finally, we hope to make the proposed method more versatile by constraining it through refining some details of this method and to prove this result through more cases.

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APPENDIX A

System	Project Indicators	Reviewer1	Reviewer2	Reviewer3	Reviewer4	Reviewer5	The Final Score
Solar panel natural wind dust removal device	Reliability	7	8	6	6	7	6.52
	Operability	6	5	6	5	7	
	Maintainability	7	6	7	6	6	
Scoring results		6.80	7.00	6.20	5.80	6.80	
Traditional waterless robot cleaning device	Reliability	8	7	7	8	7	6.44
	Operability	5	6	5	5	6	
	Maintainability	5	4	5	4	5	
Scoring results		6.80	6.20	6.20	6.60	6.40	

Table A1. Evaluation scores of the comprehensive indicator “use performance”.

System	Project Indicators	Reviewer1	Reviewer2	Reviewer3	Reviewer4	Reviewer5	The Final Score
Solar panel natural wind dust removal device	Reliability	6	6	5	6	5	5.58
	Operability	5	5	6	5	6	
	Maintainability	5	6	5	6	6	
Scoring results		5.54	5.88	5.12	5.88	5.46	
Traditional waterless robot cleaning device	Reliability	4	5	4	5	5	4.58
	Operability	4	5	5	4	4	
	Maintainability	5	5	4	5	4	
Scoring results		4.34	5.00	4.12	4.88	4.54	

Table A2. Evaluation scores of the comprehensive indicator “economic performance”.

System	Project Indicators	Reviewer1	Reviewer2	Reviewer3	Reviewer4	Reviewer5	The Final Score
Solar panel natural wind dust removal device	Reliability	7	7	6	7	8	6.37
	Operability	6	6	7	6	7	
	Maintainability	8	7	6	7	6	
Scoring results		6.63	6.37	6.63	5.37	6.85	
Traditional waterless robot cleaning device	Reliability	7	6	6	7	6	6.27
	Operability	6	6	7	6	6	
	Maintainability	6	7	6	6	7	
Scoring results		6.11	6.26	6.63	6.11	6.26	

Table A3. Evaluation scores of the comprehensive indicator “green performance”.

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