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Product Improvement Using Knowledge Mining and Effect Analogy

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Abstract: Different from new product development, design improvement aims to solve the problems of existing products. Although design knowledge and effect tools have been applied in product improvement, the existing methods for design improvement are limited in their specific application areas. A general method of product improvement is proposed in this paper using the knowledge mining and effect analogy. The length–time dimension is introduced to link the problem analysis and problem-solving for the first time. This method includes the effect knowledge base construction, length–time dimension extraction, effect retrieval, effect ranking, analogy object selection, and effect structure mapping. This method integrates a variety of algorithms and software tools in design knowledge mining to improve the efficiency of the effect analogy for product improvement. Through the comparative analysis of three effect retrieval methods and design improvement of a button battery ring device, the superiority and feasibility of the proposed method are verified.

Keywords: product improvement; effect; ontology model; analogy design; length–time (LT) dimension; knowledge mining

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1. Introduction

With the increasing market competition, the rapid evolution through improvement iterations of the product is a common practice for enterprises to maintain their product's competitive advantages [1–3]. Unlike new product development, which needs to open a whole new market, product improvement requires a well-defined prototype product to carry out the subsequent functional analysis and structural modeling for the design problems to meet user requirements.

However, existing methods of product improvement have two problems. One is their poor pertinence. Most of the product improvements use methods of new product development, such as quality function deployment (QFD) [4], axiomatic design (AD) [5], and design for six sigma (DFSS) [6]. The other methods focus on specific applications, which cannot be used for different applications. For example, the improvement method used in telecommunications equipment [7] cannot be applied to general machinery. In particular, in complex big data environments, the cost of making design decisions for enterprises is increasing [8].

Effect is a specific description of the conversion process between product input and output based on scientific principles and system attributes including physics, chemistry, biology, and geometry [9]. Effect can be used as a design tool to fully apply multidisciplinary knowledge to maximize product improvement [10]. With the support of a network database, effect can help reduce the demand for design knowledge. An effect-based method can effectively support product improvement in product development. The effect database includes knowledge of different disciplines in a wide range of products. In order to obtain the effect knowledge for high-level product innovation, Liu proposed a method of effect knowledge collection considering both characteristics of function and technical fields [11]. This method combines syntactic analysis, WordNet software, and word vector technology to extract the effect knowledge from the international patent classification text. Sheu and Hong proposed a method to identify the TRIZ solution model of design problems based on the similarity measure [12]. They summarized 70 effects and 210 known cases from science websites. Yan proposed a method to represent physical effects [13] for compatibility with the context of a particular problem to instantiate the solution model. However, the existing methods have limitations in forming the effect knowledge base, retrieving the appropriate effect, and using the effect for product improvement.

This research proposes a method of product improvement with wide application potential. The novelty of the proposed method for design improvement is as follows:

1. Ontology is introduced to represent the effect knowledge [14] and clearly define the knowledge vocabulary, relationships, and attributes to build a knowledge base for the effect expression and retrieval of the knowledge. It forms an effective tool for the effect knowledge sharing and reuse.
2. The concept of the length–time (LT) dimension is introduced to build an LT table similar to the conflict matrix. The LT dimension can effectively retrieve required design knowledge from different effects [15].
3. The analogy design method is developed to solve similar product problems by using the existing design knowledge [16]. Engineering cases of application effects are used as the knowledge resource to guide the effect analogy from two levels of function modeling and specific structure forming.

The following parts of this paper are organized as follows: Section 2 introduces basic concepts and the research status of the effect, ontology model, LT dimension, and knowledge mining and analogy design to clarify their relationships. In Section 3, a product improvement method using knowledge mining and effect analogy is proposed, including the effect knowledge base construction, LT dimension extraction, effect retrieval, effect ranking, analogy object selection, and effect structure mapping. Section 4 illustrates and verifies the superiority and feasibility of the proposed method. Comparative analyses of three effect retrieval methods and scheme acquisition of a button battery ring device are introduced. Section 5 summarizes this research and proposes future work in this area.

2. Related Research

2.1. Effect

Effect is closely related to the realization of useful functions or the replacement of harmful functions. Effect is also a measure of the use of system resources. The effect use can reduce the waste of resources for a function. Products that are designed based on the effect belong to high-level innovation [17]. The effect can be used to reduce the demand for design knowledge and improve the possibility of the birth of innovative solutions [18]. As the mechanism of effect is different from heuristic methods, in order to understand and apply effect in design improvement, this paper uses the concept–knowledge (C–K) theory for the key content and action process of the effect. C–K theory is an interdisciplinary design paradigm in the collection of design concepts and technical knowledge to gradually develop conceptual objectives and relevant parameters through mutual mapping in design spaces [19].

The action mechanism of effect explained by the C–K theory is shown in Figure 1. It includes effect space (E) and structure space (S). There are four propositions (E1, En, S1, and Sn) in the space, and four operators between propositions (E1→S1, S1→Sn, E1→En, and Sn→En). E1 stands for single effect knowledge. According to the source discipline of effects, effects can be divided into physical effects, chemical effects, geometric effects, and biological effects [20,21]. Physical effects, such as superplastic effect, are most frequently used in thermophysics. The grain structure of metal alloys has displacement, and the interatomic gravity at the displacement is weaker than that at the order. If there is enough displacement at the boundary between grains, only a small mechanical force can cause the sliding between grains, which is macroscopically manifested as deformation. In the production process of parts required by the aviation industry, tubular alloy steel needs to be deformed by gas pressure in different directions at the same time. However, ordinary hot molding cannot reach this pressure value. At this time, the raw materials can be put into a heating furnace with the appropriate pressure and temperature, and hollow parts can be made by using the superplastic effect. In order to facilitate the collection and retrieval of effects, existing research teams have established special effect libraries, including physical effect libraries, namely Oxford Creativity and Production Inspiration, and biological effect libraries, namely Biology Online and AskNature [22]. These effect libraries help the use of effects, but further development is necessary for the improvement.

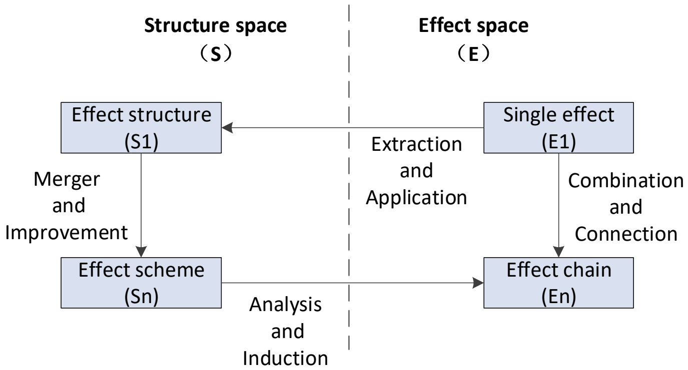


Figure 1. Mechanism of effect.

For a complete effect chain, En, design knowledge contained in a single effect is limited. Increasing the number of effects applied at the same time is required for complex product functions. For example, the bimetallic circuit breaker is based on Hooke's law and the thermal expansion effect. A plurality of causal effects can be connected with the following four effect modes [23] in the form of a circuit, as shown in Figure 2.

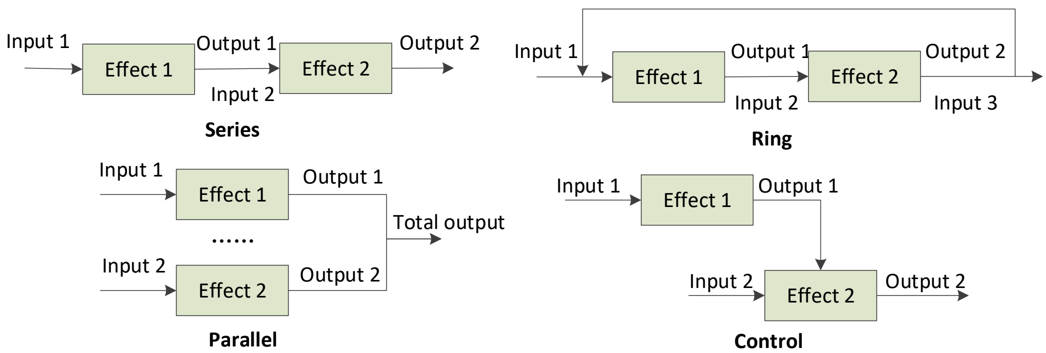


Figure 2. Four effect modes.

1. Series effect mode: the expected input and output conversion is realized by multiple effects that occur successively in sequence.
2. Parallel effect mode: the expected input and output conversion is realized by multiple effects occurring at the same time.
3. Ring effect mode: the expected input and output conversion is realized by multiple effects, and the output of the latter effect returns to the input of the previous effect in some way.
4. Control effect mode: the expected input and output conversion is realized by multiple effects, in which the output of one or more effects is controlled by the output of other effects.

Effect mode is the basic unit for the input and output conversion. In practical applications, it is usually necessary to combine multiple effect modes into a complex effect chain.

In Figure 1, S1 represents the specific effect structure, which is a physical entity containing structural features. It carries the behavior information of the product. It can also be regarded as the abstraction of component geometry with the geometric information of the product. It integrates the behavior attribute, working principle attribute, and geometric structure attribute to form the initial shape of the parts in the conceptual design stage. The specific structure obtained by the direct transformation from a single effect generally forms only a part of the scheme. For example, a grinding belt developed according to the Mobius effect can not only increase the belt length but also prolong its working life. However, the grinding belt is only the executive subsystem of the whole product, and the structure of the remaining power, transmission, and control subsystems needs to be determined by other effects. In addition, Li and Huang proposed a similar concept of the effect surface [24]. The effect surface is the geometric surface bearing the effect to carry the structural information and effect input and output information of the attached solid surface, which is convenient for the expression of the effect. In addition to studying matter, energy, and information, the effect surface also highlights the importance of positioning.

Sn represents the available effect scheme. In order to obtain the available effect scheme, the effect structure or effect surface needs to be merged. The structure is constantly improved in the process of merger, and finally, the available effect scheme is obtained. For example, in the conceptual scheme of a wolfberry picker, the air pressure effect is converted into an air pump and cylinder, the Coanda effect is converted into an air amplifier, the inertial force effect is converted into a picking head, and the venturi effect is converted into a collecting head. A large number of effect schemes have been applied in patents. With the venturi effect as the keyword, 502 relevant patents can be searched, involving different solutions in the fields of machinery, transportation, construction, and metallurgy [25]. Effect knowledge is also an important source of patents. Only 23 effects are used in the 1023 patents of the inventor Edison, and only 35 effects are used in the 1001 patents of aircraft design master Tupolev. In addition, the effect can explain the promotion of patent commercialization. For example, the structure of the biological effect of the woodpecker skull can be used to illustrate the role of the helmet in protecting the human head from severe vibration.

E1→S1 indicates that the design information is extracted from the effect and applied to the specific effect structure. On the one hand, both analogy-based design and case-based reasoning can be used to support applications of effect. On the other hand, adding corresponding engineering examples to the existing effect database can greatly reduce the difficulty of extracting design information from effect knowledge. S1→Sn indicates that multiple local effect structures or effect surfaces are combined into an optimal effect scheme. The merging process is also a screening process. In addition to considering the performance of the effect structure itself, we should also consider the compatibility between multiple effect structures. E1→En indicates that a single effect is combined into different effect modes and finally connected into a complex effect chain. There are three reasoning methods: the complete matching method, the shortest path method, and the approximate matching method [26]. Without limiting the connection length, there are many possibilities for the specific implementation of the effect chain. Sn→En means analyzing the effect characteristics from the effect scheme or effect patent and then summarizing the effect application law.

2.2. Ontology Model

The effect knowledge base assists in the storage and retrieval of information about effects. Compared to design catalog and other methods, the ontology-based knowledge representation can express the effect knowledge in a standard method, according to different knowledge categories, and store basic concepts of effect knowledge and relationships of concepts [27]. Therefore, constructing an effect database based on ontology technology can effectively solve problems of expression and storage of effect knowledge in different fields, improve the integration of effect knowledge, and facilitate the retrieval and application of effect knowledge.

Ontology is a systematic explanation or explanation of the objective existence, which pertains to the abstract essence of objective reality [28]. Ontology can be expressed as a set of five elements: C, R, I, F, and A, where C stands for class, which means everything [29]. It can be the job description, behavior definition, function expression, strategy, and reasoning process. From the perspective of semantics, it refers to a collection, which is usually explained by frame structure, concept name, and natural language. R stands for relations and refers to the interaction of some terms in the domain. From the perspective of semantics, four basic relationships are divided, including the hierarchical relationship (is_a), attribute relationship (attribute_of), dependency relationship (is_part_of), and instance relationship (instance_of). In order to solve practical problems, it is also necessary to formulate special relationships according to specific situations. I represents instances. From the perspective of semantics, objects are represented by instances. F stands for functions for a kind of specific relationship in which the nth element is unique relative to the previous $n - 1$ elements. A stands for axioms of basic facts that are not self-evident according to human rationality. For example, quantities that are equal to the same quantity are equal to each other in Euclidean geometry.

From the perspective of general domain applications, ontology has the following functions. First, the domain knowledge is analyzed, summarized, and formalized. Second, information is shared among people, machines, or both people and machines. Third, a certain degree of domain knowledge is reused. Finally, ontology can clarify domain assumptions so that domain axioms can be clearly described to reach a consensus.

With the in-depth study of ontology, some representative ontology development methods have emerged, such as the skeleton method, evaluation method, enterprise modeling method, project ontology development method, dictionary-based ontology development method, circular acquisition method, and seven steps method. Among them, the seven steps method is widely used in ontology construction [30]. Based on this method, specific steps of the ontology construction are formed as follows: (1) determining the domain and scope of ontology, (2) reusing existing ontologies, (3) listing important terms of ontology, (4) defining classes and class hierarchies, (5) defining properties of the class, (6) defining constraints for attributes, (7) and generating an instance. The specific implementation process will be shown in Section 3.1. For any domain, the ontology development process is related to its practical application, and there is no same development process.

The ontology language needs to have well-defined syntax and semantics, effective reasoning support, sufficient expression ability, and convenience of expression so as to provide a clear and formal concept description for the ontology to be constructed. With the development of the World Wide Web (Web) technology and its combination with ontology, Web-based ontology language has been widely used. As early as 2004, the World Wide Web Alliance officially recommended Ontology Web Language (OWL) as the international standard language for describing ontology in the semantic Internet [31]. Compared to other ontology languages, OWL has a richer attribute description mechanism and more semantic words. Editing tools have been developed for the development, application, and maintenance of ontology, such as Protégé [32].

2.3. LT Dimension

Dimension is a basic attribute of physical quantity [33]. The international system of units (SI) includes seven basic quantities: length, mass, time, temperature, current, amount of substance, and luminous intensity. In the field of electromagnetism, electrostatic, electromagnetic, and Gaussian systems all belong to the unit system within four dimensions [34]. The length–mass–time (LMT) system in mechanical research belongs to the unit system in three dimensions.

LT dimension is a new dimension expression to cluster physical quantities into two dimensions of time and space. Maxwell believes that physical quantities with different physical properties but consistent mathematical forms can be divided into the same category and assumes that only two basic quantities are used in the LMT dimension [35,36]. When studying mathematical relations between physical constants, Bartini used group, topology, and other theories for dimensions of mass and electric quantity as L^3T^{-2} [37]. The physical constants obtained from theoretical derivation and experimental data are approximately consistent with the scientificity of the LT dimension.

In order to use the new two-dimensional system conveniently, an LT table composed of LT dimensions was established [38]. Each cell in the LT table contains one or more physical quantities. Its row includes the length dimension from L^{-2} to L^5, and its column includes the time dimension from T^{-6} to T^3. Cells where rows and columns intersect are used to determine the dimension of a physical quantity. It is worth mentioning that the form of the LT dimension is not fixed. It can increase or reduce the physical quantity in the sub-field of physics according to the actual needs. Aleinikov [39] proposed that the LT dimension has a heuristic ability similar to the periodic table of elements in chemistry and extracted nine laws of physical conservation from it for the study of complex systems. Kuznetsov [40] even thought that some laws in ecological, economic, and social fields can be expressed by LT dimensions and also explained the impact of the LT dimension on sustainable development.

Although the LT dimension is different from the common seven dimensions, its advantages in use are significant. On the one hand, it can simplify the expression and calculation of formulas. The seven dimensions are very complex when analyzing problems because the dimension of some physical constants is not one. In the dimensional analysis, the more basic quantities a problem involves, the greater the number of calculations. If the LT dimension is adopted, there are only two basic quantities involved. In addition, the LT dimension is two-dimensional to represent the position of physical quantities in a plane rectangular coordinate system, which is more intuitive. On the other hand, we can find the internal relationship between physical quantities. There is not only one physical quantity in the cells of the LT table but also two or three or even more. This is not a random distribution but shows that there is an implicit internal relationship between these physical quantities. Taking the law of universal gravitation and Coulomb's law as examples, although they come from different fields of physics, the formulas show a high degree of consistency in their form. G and K are two constants, and the LT dimensions of m and Q are L^3T^{-2}. It can be seen that there is an internal similarity between quality and electricity in physical laws, which can be focused on in relevant research.

As a complex interdisciplinary tool, the LT dimension once made slow progress in the field of physics. However, after being introduced into the engineering field, research using the LT dimension is developing rapidly because of its objective and abstract characteristics. Bushuev [41] obtained the characteristics of key resources to solve product problems after the dimensional analysis of the TRIZ conflict model combined with the cusp catastrophe formula in catastrophe theory. He also summarized that the diagonal of the LT table reflects the substance-field evolution trend of resources and fully explained the application of the LT dimension through five practical engineering cases. Wei [42] established a parameter conversion model of the innovation problem by using the LT dimension to reduce the blindness in the use process of TRIZ. Following the new design steps, they developed a prototype of a fully automatic punching machine, which improved the production efficiency of button battery separation paper. Kotikov [43,44] expanded the LT table and applied the LT dimension to the field of transportation. He developed a transportation energy efficiency evaluation method considering speed parameters and quantitatively compared the energy efficiency indexes of heavy-duty trucks and freight railways [45]. Rajić [46,47] combined the LT dimension with TRIZ depth, resulting in synergy in the field of innovative design. The superiority of the LT dimension in solving system conflicts and obtaining ideal solutions is illustrated in the development of military equipment filter protective clothing [48].

2.4. Knowledge Mining

Knowledge mining is for the abstraction, storage, and retrieval of design resources and data. Knowledge abstraction searches for knowledge of specific targets for product improvement [49] to find similar knowledge to guide the generation of new knowledge [50]. Knowledge abstraction forms common knowledge from design resources for applications. In product design, knowledge abstraction can be divided into design knowledge abstraction and design case abstraction. The former refines the product information from the knowledge level to form new design knowledge. The latter analyzes the commonness of similar functional components for common modules of product family or product platform [51]. The degree of knowledge abstraction has the most significant impact on the novelty of design results [52,53].

Knowledge storage saves design knowledge in appropriate media according to certain rules after selecting, filtering, processing, and refining the abstracted knowledge [54]. With the rapid development of information technology, knowledge management systems generally face the difficulty of storing massive data. Zhu proposed a knowledge storage method based on a multi-indexed graph to avoid duplication of knowledge contents and optimize the parallel processing of knowledge [55]. Similarly, Yee introduced a roadmap system for knowledge generation, storage, and sharing [56]. Roadmap is a new way to store knowledge for descriptive, structured, and visual information. Jasimuddin integrated knowledge storage and knowledge transfer for the problem of asymmetric distribution of knowledge in the company [57]. Knowledge repository is crucial for future use and reference. Balch transformed expert knowledge into rules stored in the system knowledge base [58]. Numerical versions of these rules are used to analyze data and evaluate the prospects of users.

Knowledge retrieval searches the required knowledge from the database. It can be an intelligent retrieval method for knowledge association and the concept of semantic retrieval [59]. By capturing and identifying the characteristics of constructed knowledge, an ontology-based knowledge retrieval system was developed [60]. The system can prompt relevant words in the search process to reduce the difficulty of knowledge reuse. Koutsantonis proposed a method for personalized knowledge retrieval [61]. The method represents knowledge objects using an expert system for diagnosing dynamic knowledge. In order to acquire the project management knowledge accumulated in practice, Bērziša developed a set of project classification attributes to describe the characteristics of project management knowledge [62] for similarity retrieval.

Effect can be regarded as a kind of design knowledge resource. Existing studies have applied effect following the path of knowledge mining. The effect content is normally refined by professionals in related fields for the abstraction of effect knowledge. The number of abstractions can be gradually increased from a few to thousands with explanatory diagrams. Client/Server (C/S) architecture can be used for the storage of effect knowledge. As a functional module, the effect tool is integrated into computer-aided innovation (CAI) software. The effect content database is saved on a local host. Typical representatives include Goldfire Innovator, CREAX, and Innovation Tools. Because CAI software is generally available for a fee, its data scale is large and the abstraction level of knowledge is high. Another method uses the Browser/Server (B/S) architecture. The effect database is an independent website and is stored on a remote server. The advantage of the effect website is its openness and expansibility, fast update speed, and ability to be used in different places. For the retrieval of effect knowledge, the existing methods mainly focus on functions [63]. The more powerful effect library includes retrieval methods of physical quantity parameters or energy conversion types [64]. However, the use of effect and function is limited. The effect can actually be related to different factors, such as direct connections to design problems or product structure.

Although knowledge mining has received a lot of attention and is widely used, it is still in the early stage of development. There are still many research problems and challenges. In the application of effect knowledge, the problems appear in the following three aspects:

1. The process of effect abstraction lacks useful knowledge. Not all the abstracted knowledge can be used for product improvement.
2. Effect storage lacks integrity and dynamics. Effect knowledge is not independent and needs to be closely related to other contents. The update of effect knowledge is still inconvenient and cannot meet the rapid iteration of target products.
3. The results of the effect retrieval cannot meet the need for product improvement.

2.5. Analogy Design

Analogy is a way of thinking and cognitive skill from known to unknown [65]. If two objects have a similar series of attributes and one object is known to have some specific attributes, it is deduced that the other object also has similar specific attributes. Analogical thinking has played an important role in the fields of scientific discovery, economic management, and intelligent learning [66]. Analogical design uses the concept of analogy to transfer the causality and structure of source design knowledge to target design in solving problems [67]. Both case-based reasoning (CBR) and bionic design are affected by the analogy design [68]. There are three significant characteristics of the analogy design, as follows:

1. Exploratory: In the development of science, it is often necessary to use the scientific principles of other fields to describe, understand, and recognize unfamiliar knowledge with familiar knowledge so as to form new research fields and discipline theories. In this process, analogy plays an important role. Effect is the scientific principle in different fields. The essential agreement between the two makes it reasonable to apply analogy design in the process of obtaining the effect scheme.
2. Similarity: Analogy may occur when some attributes in the source design and the target design are similar or some relationships are consistent. The higher the similarity, the greater the possibility of generating analogical results. Therefore, before using the effect for analogy design, the analogy object should be selected through the similarity analysis.
3. Probability: Because analogical reasoning deduces unknown similarity from known similarity, it is reasoning from individual to individual. It lacks sufficient reason logically, and its result must have the element of speculation. Therefore, the results of analogy design cannot be directly adopted, and additional improvement or evaluation is needed.

Knowledge transfer through analogy can generate new conceptual schemes. Therefore, the analogy design has attracted great attention to finding early technical opportunities. Zhang and Yu [69] proposed a method based on analogy design and phrase semantic representation. The function of analogy design can expand the data coverage of the target field. The effectiveness of the method is verified by 3G and 4G mobile communication technology. Song [70] studied the influence of multiple analogies and irrelevant information on analogy design. On the one hand, the number of new ideas increases with the increase in the number of analogs until it reaches the saturation point. On the other hand, any analogical retrieval method can produce irrelevant information, but this information is not significant for the designer’s ability to identify analogical objects. In order to mitigate the negative impact of the design inertia, Moreno [71] described the analogy design methods, namely WordTree and SCAMPER. Through an experiment involving 97 people, it was found that these two methods can enhance the creativity of designers in the process of creative generation. Nan and Xu [72] proposed a mechanical product analogy design method based on structural similarity by using a function behavior structure shape model. Yang [73] proposed the principle of long-distance analogy design. The key to the success of analogy design is to seek unexpected discoveries (UXD) in the scenario of building a memory model in order to inspire new ideas, make the designer highlight new concepts, and finally discover and transmit UXD.

In summary, the effect, ontology model, LT dimension, and knowledge mining and analogy design form strong supports for design improvement. Effect is an important tool for product improvement. In order to apply the effect, it is necessary to establish the effect knowledge base. The establishment process of the knowledge base depends on the related research of knowledge mining, including effect abstraction, effect storage, and effect retrieval. The ontology model is a concrete representation of effect knowledge, and the LT dimension is the intermediary between effect and domain knowledge. Effect knowledge can be transformed into product structure through effect analogy.

3. Proposed Method

3.1. Effect Knowledge Base Construction

3.1.1. Abstraction of the Effect Knowledge

The object-oriented method abstracts the objective world into object classes and individuals with common attributes. Objects are connected through relationships [74]. The use of object-oriented representation has the advantages of encapsulation, modularity, inheritance, easy maintenance, and expansion. It has been widely used in the program development of various information systems. In order to facilitate the establishment of a follow-up effect knowledge base, the object-oriented ontology model is adopted in this paper. The effect knowledge base is mainly divided into four parts: the LT dimension, problem, effect, and structure. So, the corresponding ontology model is named the LT-PES model. The internal connection relationship of the LT-PES model is shown in Figure 3.

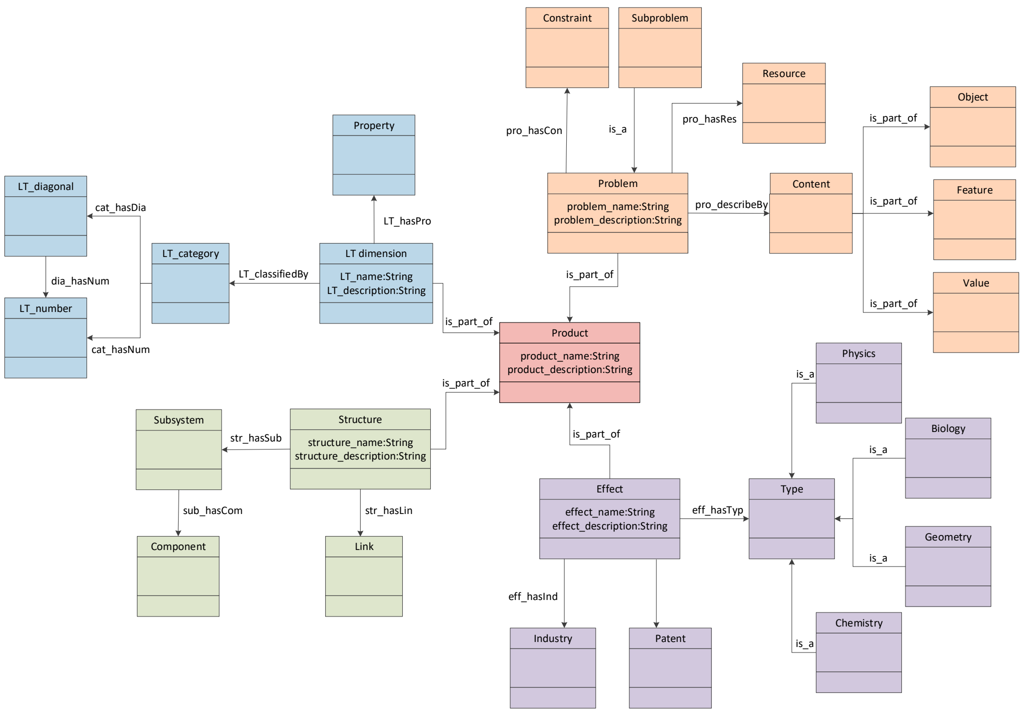


Figure 3. LT-PES ontology model.

The LT dimension part of the model includes not only the classification information of the LT dimension but also the attribute information of the corresponding physical quantity. The LT dimension is extracted from the problem analysis results; so, the problem part has the LT dimension information. The LT dimension is also the basis for effect retrieval and ranking as an index to evaluate the specific structure. It is also involved in the structure part.

The problem describes the gap between the current state and the expected state of the product. The problem part in the model represents the decomposition process of the problem. In order to solve the problem successfully, available resources and design constraints that coexist with the problem are considered. The standard description of the problem content is divided into three parts: object, feature, and value. The partial solution is also regarded as a subproblem.

The effect describes the product design knowledge, that is, the scientific principles behind the product. The effect part of the model mainly includes effect types, which are divided into physical effect, biological effect, chemical effect, and geometric effect. The effect has different design cases in different industries and is also reflected in a large number of patent documents.

The structure describes the product design results, that is, the composition of the product technology system. The structural part of the model shows the decomposability and specificity of the structure. Decomposability means that products can be divided into subsystems, and subsystems can be further divided into components. Specificity refers to the difference of structures with the same effect in different cases, which is reflected in the details of the structure and its connection relationship.

3.1.2. Storage of the Effect Knowledge

This research adds classification details and application examples to the LT-PES ontology model and builds a preliminary available effect knowledge base in Protégé. The ontology model is used as a knowledge representation to describe basic terms and relationships in related fields and form a knowledge base with individual sets of classes to provide rich multidisciplinary knowledge for product improvement.

Contents related to the LT dimension include the LT dimension classification as the result of the comprehensive division of LT dimensions from the perspective of the diagonal and number of the LT table, as shown in Table 1, and the property information, which is the collection of individual instances of 'Property' class. The 'Property' class has subclasses, namely 'Primary_Property' and 'Secondary_Property'. The two subclasses have the property 'has_secondary_property' and its inverse property 'is_secondary_property_of'. The attribute of the LT dimension is reflected by its corresponding physical quantity parameters. The attribute information is shown in Table 2.

Table 1. LT dimension classification.

Class	LT_Diagonal	LT_Number
Instance	6th diagonal	No. 1 ($L^{-2}T^{-1}$), No. 2 ($L^{-1}T^{-2}$), No. 3 ($L^{0}T^{-3}$), No. 4 ($L^{1}T^{-4}$), No. 5 ($L^{2}T^{-5}$), No. 6 ($L^{3}T^{-6}$)
	7th diagonal	No. 7 ($L^{-2}T^{0}$), No. 8 ($L^{-1}T^{-1}$), No. 9 ($L^{0}T^{-2}$), No. 1 0($L^{1}T^{-3}$), No. 11 ($L^{2}T^{-4}$), No. 12 ($L^{3}T^{-5}$), No. 13 ($L^{4}T^{-6}$)
	8th diagonal	No. 14 ($L^{-2}T^{1}$), No. 15 ($L^{-1}T^{0}$), No. 16 ($L^{0}T^{-1}$), No. 17 ($L^{1}T^{-2}$), No. 18 ($L^{2}T^{-3}$), No. 19 ($L^{3}T^{-4}$), No. 20 ($L^{4}T^{-5}$), No. 21 ($L^{5}T^{-6}$)
	9th diagonal	No. 22 ($L^{-2}T^{2}$), No. 23 ($L^{-1}T^{1}$), No. 24 ($L^{0}T^{0}$), No. 25 ($L^{1}T^{-1}$), No. 26 ($L^{2}T^{-2}$), No. 27 ($L^{3}T^{-3}$), No. 28 ($L^{4}T^{-4}$), No. 29 ($L^{5}T^{-5}$)
	10th diagonal	No. 30 ($L^{-2}T^{3}$), No. 31 ($L^{-1}T^{2}$), No. 32 ($L^{0}T^{1}$), No. 33 ($L^{1}T^{0}$), No. 34 ($L^{2}T^{-1}$), No. 35 ($L^{3}T^{-2}$), No. 36 ($L^{4}T^{-3}$), No. 37 ($L^{5}T^{-4}$)
	11th diagonal	No. 38 ($L^{-1}T^{3}$), No. 39 ($L^{0}T^{2}$), No. 40 ($L^{1}T^{1}$), No. 41 ($L^{2}T^{0}$), No. 42 ($L^{3}T^{-1}$), No. 43 ($L^{4}T^{-2}$), No. 44 ($L^{5}T^{-3}$)
	12th diagonal	No. 45($L^{0}T^{3}$), No. 46($L^{1}T^{2}$), No. 47($L^{2}T^{1}$), No. 48($L^{3}T^{0}$), No. 49($L^{4}T^{-1}$), No. 50($L^{5}T^{-2}$)

Table 2. Attribute information.

Class	Primary_Property	Secondary_Property
Instance	Concentration	Concentration gradient, concentration, humidity, and composition
	Quantity	Quality, quantity, weight, size, and price
	Chemical	pH value, chemical formula, corrosivity, solubility, and odor
	Force	Friction coefficient, friction heat, and torque
	...	...

Contents of relevant questions to be entered include the following: (1) Available resources: Resources are the general name of all materials, energy, and information that can be developed and utilized by human beings. Resources include material resources, energy resources, field resources, information resources, space resources, and time resources. (2) Design constraints: Objective conditions that hinder the normal function of the product or make the new scheme not feasible, such as the purchase cost, operation energy consumption, occupied space, and processing noise. (3) Subproblem: The decomposition process of the initial problem is recorded. The standardized description of the problem includes objects, features, and values. The parameters that affect the importance of the subproblem are determined by the product problem itself.

Contents related to effects include (1) effect classification, as shown in Table 3. In the field of conceptual design, physical effect is clearly defined as the existence of physical laws for the physical effects and system functions combined closely. The class 'Type' has subclasses, namely 'Primary_type' and 'Secondary_type', and the two subclasses have the object attribute 'has_secondary_type' and its inverse attribute 'is_secondary_type_of'. (2) Industry classification is constructed based on the manufacturing industry in the national economic industry classification of the National Bureau of Statistics [75], which is used to distinguish different manifestations of the same effect in different industries. (3) Patent information, i.e., patent documents that record the use results of effects, can be queried and imported from the free national patent office database or the secondary developed commercial database according to design needs.

Table 3. Effect classification.

Class	Primary_Type	Secondary_Type
Instance	Physical effect	Hopkinson effect, Barkhausen effect, Joule Thomson effect, Peltier effect, Magnetocaloric effect, Thermoelectric effect, Photoelectric effect, Doppler effect, etc.
	Biological effect	Lotus leaves are self-cleaning, Dragonfly wings are vibration-damping, Shells reduce wear, Camel hooves travel on soft soil, etc.
	Chemical effect	Thermochromic reaction measures temperature, Chemiluminescence carries out object positioning, Semi-permeable membrane controls liquid movement, etc.
	Geometric effect	The Mobius effect reduces the material loss, The rotating hyperboloid effect changes the diameter, etc.

Contents related to the structure include (1) subsystems and components, as shown in Table 4. A complete technical system can be roughly divided into the energy subsystem, transmission subsystem, execution subsystem, and control subsystem according to functions undertaken by internal components. (2) The connection relationship, that is, the individual collection of the class 'Link', represents the connection mode between structures. Common connection relationships include threaded connections, flange connections, pin connections, and so on.

Table 4. Component classification.

Class	Subsystem	Component
Instance	Energy	Motor, External combustion engine, Steam turbine, etc.
	Transmission	Chain, Rope, Shaft, Pulley, Cam, Gear, Piston, etc.
	Execution	Servo motor, Electromagnetic brake, Hydraulic motor, etc.
	Control	Valve, Gauge, Knob, Indicator, Nozzle, etc.

All the above contents are input into Protégé in order. When the effect knowledge base is constructed, the consistency of ontology syntax, semantics, and user-defined content needs to be checked. Generally, ontology description documents are directly generated by software tools without syntax inconsistency. The consistency of user-defined content needs to be evaluated by experts based on their domain expertise. Therefore, the ontology consistency check mainly refers to the semantic consistency check. Various inference engines can support the OWL semantic consistency check. The latest version of Protégé has a built-in Hermit inference engine, which can determine whether the ontology is consistent and identify the implicit relationship between classes according to OWL files.

3.2. LT Dimension Extraction

Even when product problems are obvious, the root causes of the problems are often not fully understood. For problem analysis, a variety of root cause mining tools have been developed. The characteristics and scope of applications of these tools are different, as shown in Table 5. According to the actual situation, one or more appropriate tools can be used to develop strengths and avoid weaknesses. After the root causes of problems are determined, LT dimensions need to be extracted to lay the foundation for the retrieval, ranking, and mapping of subsequent effects. Manual extraction results are largely affected by the personal analysis ability and physical knowledge level. Moreover, the root cause and LT dimension are not exactly one-to-one correspondence. There will be cases where one root cause involves multiple LT dimensions, and there will be cases where multiple root causes only correspond to a single LT dimension. If there are omissions or corresponding errors in the extraction results of the LT dimension, the subsequent improvement process will be unreliable. Therefore, the text classification function of natural language processing software NLPIR-Parser is used to automatically extract the LT dimension, which also eliminates the step of frequently querying the LT table.

Table 5. Comparison of root cause analysis tools.

Tool	Application Scope	Advantage	Insufficient
Function analysis [76]	The number of components is small, and the relationship is clear.	Avoid jumping cause finding and strict causal logic.	Limited to component relationship analysis in the technical system.
Fishbone diagram [77]	It is mostly used for the qualitative problem analysis of team operations.	Multi-angle analysis of the problem is more comprehensive and easy to understand.	The relationship between factors cannot be identified, and there is no mechanism to select root causes.
Current reality tree [78]	The close relationship within the system.	It shows the interdependence between causes and has a logical test mechanism.	It requires high logic and takes a long time.
5W1H [79]	Analyze the root cause of the problem by one person.	Overcome their own subjective judgment and logical inertia and gradually look for the cause of the problem.	When too many factors are involved in a complex system, it is impossible to find the root cause.
Fault tree method [80]	It is mostly used for engineering risk assessment and fault diagnosis.	Clear thinking, qualitative analysis, and quantitative analysis.	Only analyze specific accidents, not a process or technical system.

There are two modes of text classification in NLPIR-Parser: deep learning classification and expert rule classification. Deep learning classification uses software self-learning for system classification through a large number of text training. For example, according to the dimensional analysis and physical quantity knowledge, a large number of relevant texts are prepared for each LT dimension as a corpus. Through training, the software automatically learns category features. After continuous corpus training, the classification accuracy is increased. The F-measure value of the comprehensive open test by the software is close to 86% [81].

The expert rule classification refers to the classification according to classification rules formulated in advance. The software determines its LT dimension classification according to words appearing in the root cause text. The rule content can be written with four logical operation symbols: AND, OR, NOT, and NEAR, where NEAR specifies the number of bytes between the two words. Fields can be written with TITLE, CONTENT, AUTHOR, and DATATYPE. The latter two fields only support the OR operator. The minimum word frequency tree condition can be set in the rule, that is, the minimum required number of occurrences of all the words in the condition field in the original field. Currently, it supports rules at or below two levels. Sub-rules support AND, OR, and NOT. For example, '(momentum OR energy OR temperature)/CONTENT/2 NEAR 10 (change OR decrease OR increase OR measure OR maintain)/CONTENT/1' means that in the root cause document, the distance between any word in two groups and any word in the other group is within 10 bytes, and the co-occurrence frequency is at least once. This rule focuses on the contents of three physical quantity parameters in the root cause so as to classify them into the dimension L5T-4 set. In order to obtain the most accurate LT dimension, extraction results of the two classification patterns are comprehensively considered in this paper.

3.3. Retrieval of the Effect Knowledge

With the help of the close relationship established by the LT-PES model, the effect retrieval mechanism based on the LT dimension is formed, as shown in Figure 4, using the following five steps. (1) The LT dimension is input into the effect knowledge base. The LT dimension comes from the NLP extraction result of the root cause of the problem. Because of the abstraction of the LT dimension, one LT dimension mostly corresponds to multiple physical quantities for query expansion [82]. (2) Constraints are applied for more applicable results. It also reduces the interference of irrelevant content. Specific constraints come from the problem part, effect part, and structure part of the model, such as design constraints, industry, and available resources. (3) The retrieval link obtains the qualified effect information from the established effect knowledge base. (4) The number of retrieval results is decided. Effect knowledge can be treated as an information block for processing, following Miller's law in product design, which limits the number of effect searches from five to nine. A small number is not enough to support the divergence of design thinking. We can gradually reduce restrictions and repeat the retrieval steps until the regulations are met. When the quantity is too large, the physical quantity parameters involved can be further defined in limiting conditions. Retrieval steps can also be repeated. (5) The math algorithm is used to rank alternative results. Finally, one or more effects with the highest availability are the design output.

Ranking retrieval results is also a research branch of knowledge retrieval. Different from products or schemes with a complete structure, effect mainly provides abstract knowledge information. At present, effect ranking is still a complex and difficult process. Although the decision-making process relying on experts from internal or external consulting companies is common, it is highly subjective. Therefore, it is necessary to introduce mathematical tools to increase the reliability of ranking results.

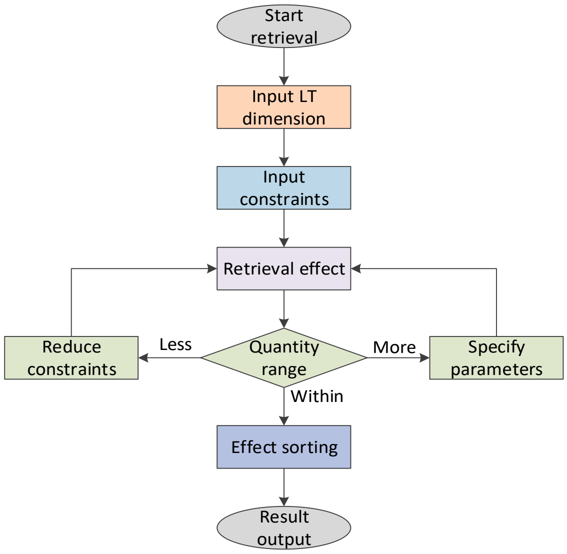


Figure 4. Effect retrieval mechanism.

In the process of ranking the effects, experts provide an opinion range. Therefore, fuzzy numbers express expert views rather than exact numbers, and, in particular, triangular fuzzy numbers are most widely used [83]. A triangular fuzzy number effect ranking method based on fuzzy ordered weighted averaging (FOWA) [84] is formed. The method includes the following five steps to retain the advantages of paired comparison assignment and reduce information loss in the concept score matrix [85], coefficient of variation [86], and Dempster combination rule [87].

Step 1: Assuming that retrieval results of effects are n, indexes i and j have the same value range 1, 2, . . ., n. Through the pairwise comparison of these effects, a complementary evaluation matrix $\widetilde{A} = (\widetilde{a}_{ij})_{n \times n}$ composed of triangular fuzzy numbers is formed. The value of each element $\widetilde{a}_{ij} = (a^L_{ij}, a^M_{ij}, a^U_{ij})$ in the matrix $\widetilde{A}$ is the common opinion of the expert group, and $a^L_{ij} + a^U_{ji} = a^M_{ij} + a^M_{ji} = a^U_{ij} + a^L_{ji} = 1$, $a^L_{ii} = a^M_{ii} = a^U_{ii} = 0.5$, and $a^U_{ij} \geq a^M_{ij} \geq a^L_{ij}$ are specified.

Step 2: Selecting appropriate fuzzy semantic quantization criteria to obtain the value of parameter pair (a, b) in the corresponding operator Q. There are three common criteria, namely, maximum (0.3, 0.8), at least half (0, 0.5), and as much as possible (0.5, 1). r is an intermediate parameter whose relative value is determined by j/n and $(j-1)/\text{n}$ in Equation (1). The weighting vector ω_j can be obtained by Equations (1) and (2) [88].

Step 3: Deciding risk parameters $\lambda \in [0, 1]$. The more conservative the experts are, the smaller the value of λ. Each element $\widetilde{a}^{(\lambda)}_{ij}$ in the expected value matrix $\widetilde{A}^{(\lambda)}$ is calculated by Equation (3).

Step 4: Recording the matrix $\widetilde{A}$ according to the expected value in the matrix $\widetilde{A}^{(\lambda)}$, and the obtained matrix is named $\widetilde{B}$. According to Equation (4), degree $\widetilde{d}_i$, that is, each effect that is superior to other effects, can be quantitatively obtained, and the new matrix $\widetilde{D}$ is composed of a set of $\widetilde{d}_i$.

Step 5: Using Equation (3) again to obtain the expected value matrix $\widetilde{D}^{(\lambda)}$ of matrix $\widetilde{D}$. After normalization, a ranking vector ω' is obtained. The priority of effect analogy is determined by the ranking vector.

$$\omega_j = Q(j/\text{n}) - Q[(j-1)/\text{n}] \tag{1}$$

$$Q(r) = \begin{cases} 0, & r < a \\ \frac{r-a}{b-a}, & a \leq r \leq b \\ 1, & r > b \end{cases} \tag{2}$$

$$\widetilde{a}_{ij}^{(\lambda)} = \frac{1}{2}[(1-\lambda)a_{ij}^{L} + a_{ij}^{M} + \lambda a_{ij}^{U}] \tag{3}$$

$$\widetilde{d}_i = \omega_1 \times \widetilde{b}_{i1} + \cdots + \omega_n \times \widetilde{b}_{in} \tag{4}$$

3.4. Effect Scheme Acquisition

3.4.1. Analogy Object Selection

One effect often corresponds to multiple actual engineering cases. The analogy for all cases in the knowledge base is inefficiency. In order to quickly and accurately find the most relevant analogy objects, cases need to be screened according to the problems of the target product. The similarity analysis between the engineering case and the target product is the premise of analogy design. According to the research in reference [89], the similarity between the two concepts can be expressed as the cosine value of the vector in n-dimensional Euclid space.

Combined with the above mathematical principles, a case similarity calculation method based on the LT dimension is proposed. The specific application process of this method includes five steps. (1) The index number of the LT dimension in the problem root cause and engineering case is expressed in the form of a vector. The LT dimension of the problem root cause is extracted by NLPIR-Parser, and the LT dimension of the engineering case is recorded in the effect knowledge base. (2) The LT dimension feature set for the pairwise comparison is constructed to divide it into problem set P and case set C. Each element in the set is the modulus of the corresponding exponential vector, and the order is numbered according to the LT dimension. (3) Sets P and C are merged to obtain a new set U. Then, P and C intersect with U to obtain new sets P′ and C′, respectively, and the missing positions are filled with 0. (4) Equation (5) is used to calculate the similarity of cases, keeping two decimal places for the calculation results. Cases in the knowledge base are sorted by similarity. The cases with high similarity are more likely to produce effect schemes for the priority. If the number of analogy objects obtained by the first effect cannot meet the needs of the conceptual design, it can continue to screen in the engineering case base of the next effect according to the ranking results of effects.

The parameters in Equation (5) are explained through examples of wind turbines and liquid flow meters. The former is the target product, and the problematic LT dimensions are [L^1T^{-1}] and [L^5T^{-5}]. The latter is an analogy object, and the LT dimensions are [L^2T^{-4}] and [L^5T^{-5}]. They are converted in the order of the vector form (1, −1), (5, −5), (2, −4), and (5, −5). Therefore, P = ($\sqrt{2}$, $\sqrt{50}$) and C = ($\sqrt{20}$, $\sqrt{50}$). The two newly processed sets are P′ = (0, $\sqrt{2}$, $\sqrt{50}$) and C′ = ($\sqrt{20}$, 0, $\sqrt{50}$). After substituting P′ and C′ into Equation (5), the similarity is calculated as 0.83.

$$Sim(P',C') = \frac{p_1'c_1' + \cdots + p_k'c_k'}{\sqrt{(p_1')^2 + \cdots + (p_k')^2} \times \sqrt{(c_1')^2 + \cdots + (c_k')^2}} \tag{5}$$

3.4.2. Effect Structure Mapping

Structure mapping theory is the research result of analogy design for relational structure problems. Its key idea is to extract the structure between various factors in the source design, match it with the structure of the target design, and use the solution method of source problems to solve the target problem [90,91]. Structural mapping occurs at multiple levels, such as surface features, attributes, and relationships. Based on this theory, an analogy process is proposed to transfer effect knowledge from the original technology system to the target product. The effect analogy mechanism is as follows.

Selected effect: Case of the effect <=> Root cause of the problem: Scheme structure

Taking the bridge erecting machine as an example [92], the analogy process from the engineering case to the conceptual structure is introduced. As shown in Figure 5, it is generally divided into four steps.

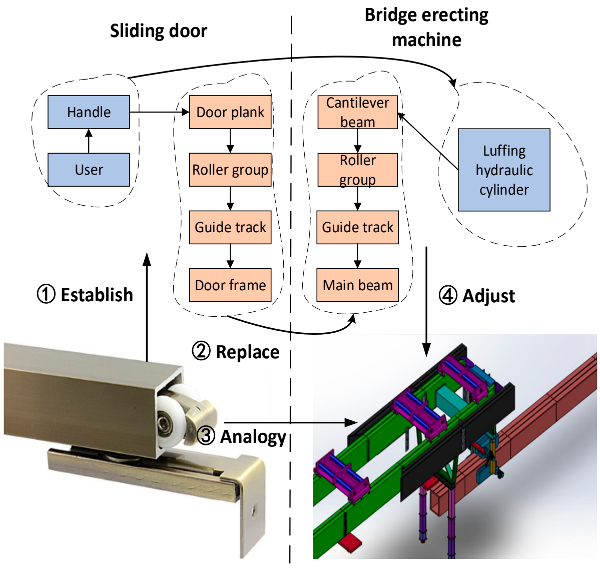


Figure 5. Effect structure mapping process.

Step 1: Exporting the knowledge information of the project case from the effect knowledge base, including the function model and appearance drawing. Some engineering cases are reused for the first time, and their function models need to be built temporarily. The function model of the target product has been established in the process of root cause analysis.

Step 2: Marking components in the engineering case that reflect the effect or achieve the expected function and replace the problematic components of the target product with them so as to form the function model of the effect scheme. For example, the power of the sliding door is provided by the user pushing the handle, while the bridge erecting machine uses a variable amplitude hydraulic cylinder to provide stable power. The roller structure on the sliding door is fixed on the door panel and door frame, and the roller structure of the bridge erecting machine is installed between the cantilever beam and the main beam.

Step 3: Combining the industry field of the target product to compare the structural modeling and obtain the preliminary scheme. Products used in an urban environment need to consider aesthetics and ergonomics, while equipment installed in the field will pay more attention to service life and reliability.

Step 4: Comparing the preliminary scheme with the new function model to understand the internal action relationship between components through the function model so as to adjust the structural details of the preliminary scheme. It may be limited by objective conditions as some structures cannot be realized. At this time, it is necessary to adjust the function model in reverse and carry out two or more iterations. Finally, the newly established function model and conceptual structure are saved in the bridge erecting machine case of the effect knowledge base.

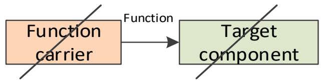
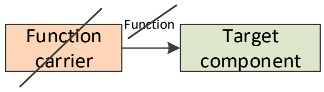
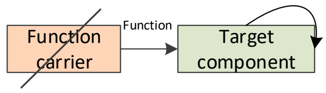
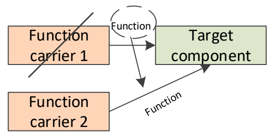
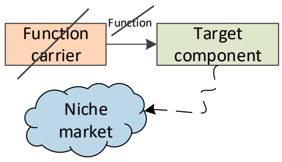
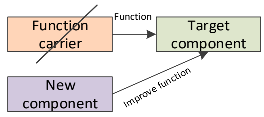
3.4.3. Effect Structure Trimming

Although the scheme obtained by structure mapping uses the effect to solve the product problem, there may be a waste of system resources in the mapping process. In order to increase the economy of the scheme and reduce the burden of subsequent manufacturing and assembly, the effect structure can be optimized by trimming [93]. Trimming is an improvement method based on the function model to remove some components in the system and reallocate resources in the system or supersystem to ensure the normal realization of functions [94,95]. The objectives of trimming include simplifying the structure, reducing costs, removing negative functions, and even fundamentally avoiding competitors' patents [96,97].

Before trimming the effect structure, it is necessary to determine the trim order and which component should be used to start trimming; then, the remaining components are trimmed according to the order. The component to be trimmed preferentially shall have one or more of the following characteristics [98]: (1) Key negative factors: The root cause of the system problem is the key negative factor. Components in the final conflict area determined on the function model should be trimmed first. (2) The most harmful function: The harmful function analysis of components can be obtained. Components that cause the most harmful functions in the system should be taken as the primary trimming object. (3) The most expensive component: Using cost analysis, components with high cost and little function can be cut off, which can greatly reduce the manufacturing cost of the system.

Rules are also followed in the process of trimming, as shown in Table 6 [99]. Priorities of different trimming rules are different, and the priorities are arranged in alphabetical order. In this scenario, trimming rules should match the priorities. The trimmed effect structure becomes an effect scheme with high availability.

Table 6. Trimming rules.

Rule	Content	Sketch Map
A	Delete the function of the original component.	
X	Delete the function performed by the original component.	
B	The functions performed by the original element are performed by the affected element itself.	
C	The functions performed by the original components are performed by other components or super systems.	
D	If a new niche market can be found and the trimmed system can make huge profits, the current function provider can be removed.	
E	Find new components outside the system to replace the current function provider.	

3.5. Summary

This section introduces a product improvement method using knowledge mining and effect analogy, including the following six steps, as shown in Figure 6: (1) Effect knowledge base construction: An LT-PES ontology model is formed by connecting problems, effects, and structures with the LT dimension. The effect-related information is input and stored in the database software to preliminarily build an available knowledge base. (2) LT dimension extraction: The classification rules of natural language processing are constructed by using the LT dimension knowledge. Appropriate root cause analysis tools are used to obtain the root cause of the problem and input root causes into NLPIR-Parser in text form. (3) Effect retrieval: Based on information retrieval theory, an effect retrieval mechanism is formed. The LT dimension and other constraints are input into the knowledge base to obtain multiple related effects. (4) Effect ranking: The expert group scores the effect obtained in the previous step, and the triangular fuzzy number obtained is substituted into the FOWA algorithm. Matlab is used to simplify the calculation process, and the availability ranking of effects is then obtained. (5) Analogy object selection: The root cause of the problem and the LT dimension of the engineering case are substituted into the similarity calculation equation. The appropriate analogy object is selected according to the similarity. (6) Effect structure mapping: Following the effect analogy mechanism, the product function model is replaced by an analogy of the specific structure of the product. The conceptual scheme obtained at this time solves the product problem to a certain extent, but there is still a chance for simplifying the structure and saving resources. According to the trimming order and trimming rules, the effect structure is trimmed to obtain a higher idealized effect scheme. More effect schemes can be obtained by expanding the effect search scope or adding analogy objects. These effect schemes can be screened or combined according to different needs.

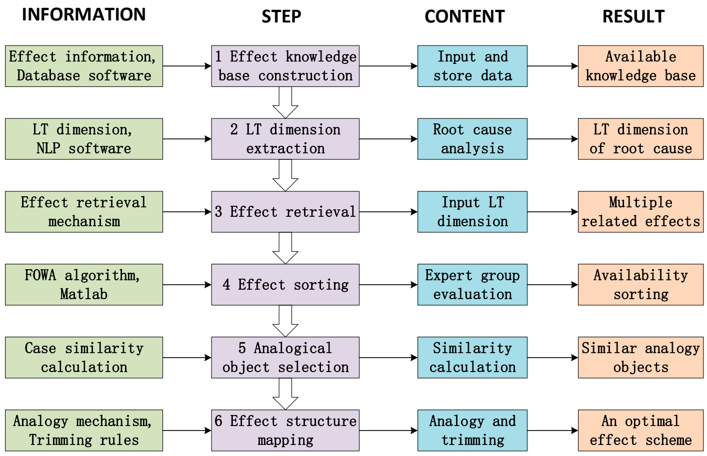


Figure 6. Process of the proposed method.

4. Method Validation

4.1. Comparative Analysis of Effect Retrieval Methods

In order to verify the proposed effect retrieval method based on the LT dimension, a relevant comparative analysis is conducted. The participants are graduate students from the School of Mechanical Engineering at a well-known university in China. They are divided into three groups, with five males and five females in each group, to select appropriate effects for ten engineering cases. Standard answers to these cases have been collected in advance, as shown in Table 7. These cases all originated in Tianjin, China. The participants promise not to understand the cases in other ways. Group A mainly relies on its own experience and can consult books on the effects provided by the author. Group B uses the existing network database. Group C uses the new effect knowledge base, and members of the group act as experts for each other. Finally, the participants filled in the questionnaire with the effect of their own retrieval. The process took 100 min.

Table 7. Retrieve objects.

No.	Case Name	Effect Number
I	Injection mechanism of injection molding machine	4
II	Belt conveyor idler	5
III	Electric manipulator cotton picker	6
IV	Solar heater	6
V	Automatic water-collecting equipment	5
VI	Hypnotic mosquito repellent device	2
VII	Automatic storage device	3
VIII	Hot melt butt welding machine	4
IX	Traditional Chinese medicine dropping pill machine	8
X	Quick shut-off valve	4

Collected questionnaires are processed uniformly. The following measures are applied to evaluate the obtained results: recall, precision, and F_1-measure. The number of relevant effects is fixed, but the number of effects retrieved varies per student. Recall is the percentage of the number of retrieved effects related to the case and the number of all relevant effects. Its value measures whether retrieved effects are comprehensive, as shown in Equation (6). Precision is the percentage of the number of effects retrieved related to the case and the number of all effects retrieved. Its value measures whether the retrieved related effects are accurate, as shown in Equation (7). When the results of the recall and precision are inconsistent, the F_1-measure value is used to solve the conflict between them, as shown in Equation (8). It is a weighted harmonic number of the recall and precision to evaluate retrieval results more objectively.

$$Recall = \frac{|\{retrieved\} \cap \{relevant\}|}{|\{relevant\}|} \tag{6}$$

$$Precision = \frac{|\{retrieved\} \cap \{relevant\}|}{|\{retrieved\}|} \tag{7}$$

$$F_1\text{-}measure = \frac{2 \times Precision \times Recall}{Precision + Recall} \tag{8}$$

Figure 7 shows the comparison of recall results of the three groups. The ordinate of each point on the polyline is the average of the recall rate of ten members in the group. The three groups of data were analyzed by a one-way analysis of variance (ANOVA) using the Bonferroni method [100], and the results are shown in Table 8. There was a significant difference in the recall rate between group A, group B, and group C (p < 0.05). The recall rate of group A was the lowest, no more than 50%. There was no significant difference between group B and group C (p > 0.05), but the value of the latter was relatively higher.

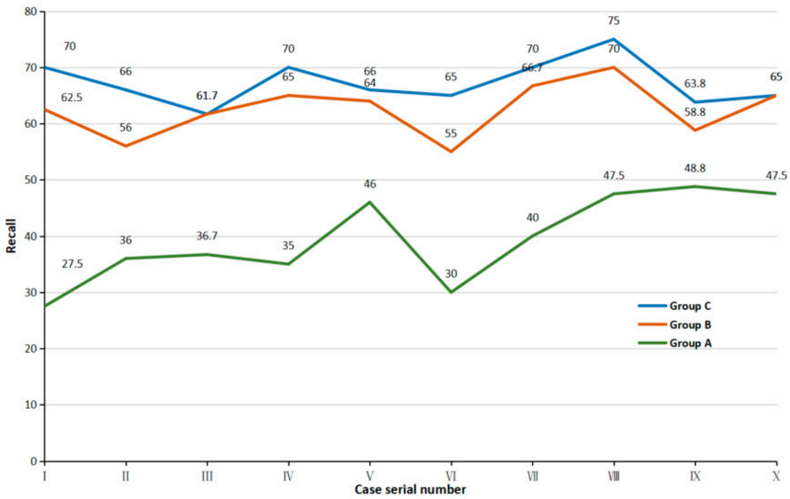


Figure 7. Comparison of average recall.

Table 8. One-way ANOVA of recall.

Group	Group	Mean Difference	Std. Error	Sig. (p-Value)
A	B	−5.190	4.6935	0.279
C	A	22.340	4.6935	0.000
C	B	17.150	4.6935	0.003

Figure 8 shows the comparison of the accuracy results of the three groups. The ordinate of each point on the polyline is the average of the precision rate of the ten members in the group. The Bonferroni method was also used for a one-way ANOVA on the three groups of data, and the results are shown in Table 9. There was a significant difference in the precision rate between group C, group A, and group B, and the precision rate of group C had obvious advantages. There was no significant difference between group A and group B.

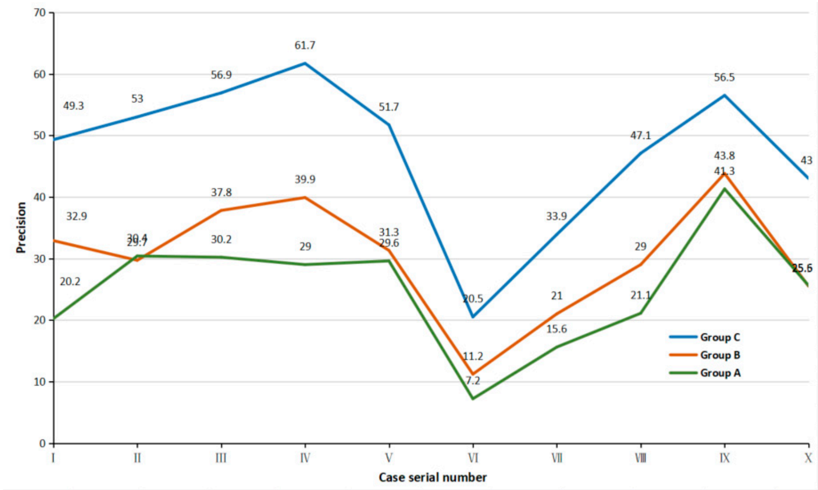


Figure 8. Comparison of average precision rate.

Table 9. One-way ANOVA of precision rate.

Group	Group	Mean Difference	Std. Error	Sig. (*p*-Value)
A	B	−5.190	4.6935	0.279
C	A	22.340	4.6935	0.000
C	B	17.150	4.6935	0.003

Taking into account the overall results of recall and precision, the following conclusions can be drawn without using the F-measure. (1) In the process of retrieval effect, it is not advisable to rely only on the designer's own experience. This is also the main reason that effect tools are less used in TRIZ and that the user feedback is poor. (2) The existing network database can effectively help users retrieve a sufficient number of effects, but it will also bring more useless data and insufficient accuracy of the retrieval results. (3) The effect retrieval mechanism based on the LT dimension can ensure high recall and precision at the same time for product improvement.

4.2. Case Study of the Button Battery Ring Device

4.2.1. Analysis of Existing Problems

Button batteries are widely used in micro-electronic products, composed of electrode materials, diaphragm paper, electrode liquid, and other components [101]. The positive and negative poles of the battery are separated by a sealing ring to insulate and prevent electrode liquid leakage. The button ring device of button batteries is used to insert the sealing ring coated with glue into the circular cathode steel ring of the batteries. An existing device consists of a horizontal workbench, feeding mechanism, cylinder, vacuum generator, suction cup, and other subsystems, as shown in Figure 9. The motor and air pump are located on the lower platform. Based on the manufacturer's feedback, the device has a high cost and low production efficiency. It is required to retrieve an improvement solution by the effect knowledge base.

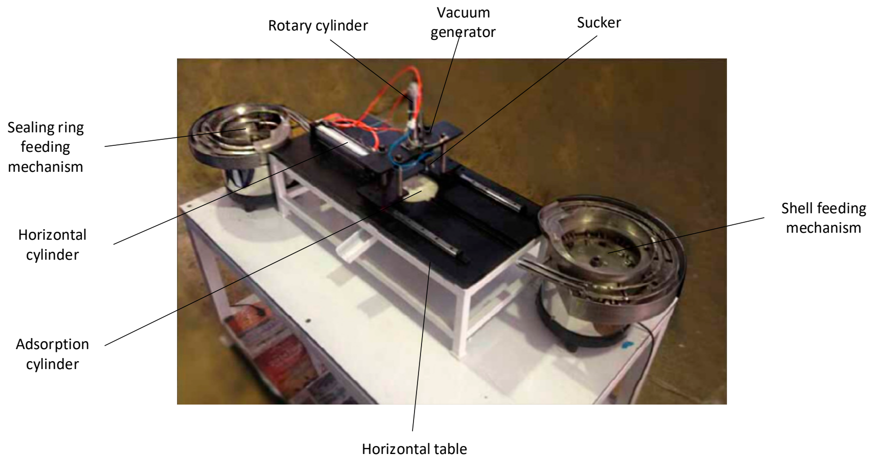


Figure 9. Existing button battery ring device.

The functions are analyzed for the button battery ring device. A function model of the existing product is constructed, as shown in Figure 10. It can be found that there are not only problems in the assembly process of sealing the ring and the shell but also deficiencies in the movement process of the two components. After further analysis, the root causes of the problem were found, as follows: (1) The execution cycle time of the buckle action is long. According to the measurement, the average time is 6 s. (2) The device needs to move back and forth horizontally as a whole, and the energy consumption of the motion mechanism is relatively high. (3) The device has a large volume and thus needs an independent working space. (4) The equipment contains an electrical coupling device, and the control is complex. The contents of the above root causes are input into NLPIR-Parser to obtain the corresponding LT dimensions of No. 16 (L^0T^{-1}), No. 27 (L^3T^{-3}), No. 37 (L^5T^{-4}), and No. 48 (L^3T^0).

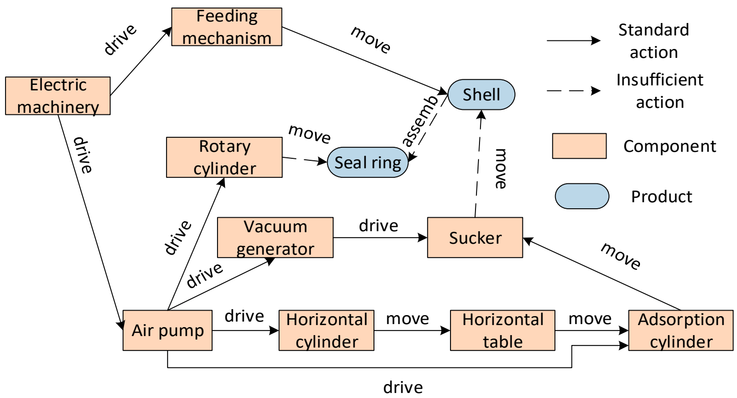


Figure 10. Function model of button battery ring device.

4.2.2. Effect Knowledge Retrieval and Ranking

Following the effect retrieval mechanism introduced in Section 3.3, the LT dimension obtained in the previous step is input into the effect knowledge base. For products made by the metal processing, general equipment manufacturing, electrical machinery manufacturing, electronic equipment manufacturing, and instrument manufacturing industries, the available resources are a power supply, a wide room, a workbench, an air pump, and a cylinder. The design constraints are high production efficiency and a low defective rate. The effect search results are shown in Table 10. The quantity is the specified interval.

Table 10. Effect retrieval results.

No.	Name	Content	Case
1	Rotation effect	Rotating geometry may obtain better performance, such as the rotation of the original stationary structure.	Rotary tube machine gun
2	Thermal expansion effect	When the external pressure is constant, the volume of most substances increases when the temperature increases and decreases when the temperature decreases.	Rodless cylinder
3	Electromagnetic induction	Conductors placed in varying magnetic flux produce electromotive force. If the conductor is closed into a loop, the electromotive force will drive electrons to flow and form an induced current.	Electromagnetic relay
4	Hooke's law	After a solid material is stressed, there is a linear relationship between stress and strain in the material.	Spring scale
5	Pascal effect	The pressure added to any part of the closed liquid must be transmitted from the liquid to all directions according to its original size.	Lifting jack

According to the expected availability of the effect principle in the button battery ring device, the expert group compares the above five effects in pairs and constructs a triangular fuzzy complementary judgment matrix, as follows:

$$\widetilde{A} = (\widetilde{a}_{ij})_{5\times 5} = \begin{bmatrix} (0.5,0.5,0.5) & (0.5,0.6,0.8) & (0.7,0.8,0.9) & (0.5,0.7,0.8) & (0.6,0.8,0.9) \\ (0.2,0.4,0.5) & (0.5,0.5,0.5) & (0.5,0.8,0.9) & (0.5,0.7,0.8) & (0.6,0.7,0.8) \\ (0.1,0.2,0.3) & (0.1,0.2,0.5) & (0.5,0.5,0.5) & (0.1,0.2,0.3) & (0.2,0.3,0.5) \\ (0.2,0.3,0.5) & (0.2,0.3,0.5) & (0.7,0.8,0.9) & (0.5,0.5,0.5) & (0.2,0.4,0.5) \\ (0.1,0.2,0.4) & (0.2,0.3,0.4) & (0.5,0.7,0.8) & (0.5,0.6,0.8) & (0.5,0.5,0.5) \end{bmatrix}$$

The fuzzy semantic quantization criterion is maximum $Q = (0.3, 0.8)$, which is substituted into Equations (1) and (2) to obtain the weighted vector $\omega = (0, 0.2, 0.4, 0.2, 0)^T$ of the FOWA operator. If the expert decision risk $\lambda = 0.5$, the expected value matrix is obtained according to Equation (3), as follows:

$$\widetilde{A}^{(0.5)} = \begin{bmatrix} \widetilde{a}_{11}^{(0.5)} = 0.500 & \widetilde{a}_{12}^{(0.5)} = 0.625 & \widetilde{a}_{13}^{(0.5)} = 0.800 & \widetilde{a}_{14}^{(0.5)} = 0.675 & \widetilde{a}_{15}^{(0.5)} = 0.775 \\ \widetilde{a}_{21}^{(0.5)} = 0.375 & \widetilde{a}_{22}^{(0.5)} = 0.500 & \widetilde{a}_{23}^{(0.5)} = 0.750 & \widetilde{a}_{24}^{(0.5)} = 0.675 & \widetilde{a}_{25}^{(0.5)} = 0.700 \\ \widetilde{a}_{31}^{(0.5)} = 0.200 & \widetilde{a}_{32}^{(0.5)} = 0.250 & \widetilde{a}_{33}^{(0.5)} = 0.500 & \widetilde{a}_{34}^{(0.5)} = 0.200 & \widetilde{a}_{35}^{(0.5)} = 0.325 \\ \widetilde{a}_{41}^{(0.5)} = 0.325 & \widetilde{a}_{42}^{(0.5)} = 0.325 & \widetilde{a}_{43}^{(0.5)} = 0.800 & \widetilde{a}_{44}^{(0.5)} = 0.500 & \widetilde{a}_{45}^{(0.5)} = 0.375 \\ \widetilde{a}_{51}^{(0.5)} = 0.225 & \widetilde{a}_{52}^{(0.5)} = 0.300 & \widetilde{a}_{53}^{(0.5)} = 0.675 & \widetilde{a}_{54}^{(0.5)} = 0.625 & \widetilde{a}_{55}^{(0.5)} = 0.500 \end{bmatrix}$$

The elements in the complementary judgment matrix are reordered according to the matrix size.

$$\widetilde{B} = (\widetilde{b}_{ij})_{5\times 5} = \begin{bmatrix} (0.7,0.8,0.9) & (0.6,0.8,0.9) & (0.5,0.7,0.8) & (0.5,0.6,0.8) & (0.5,0.5,0.5) \\ (0.5,0.8,0.9) & (0.6,0.7,0.8) & (0.5,0.7,0.8) & (0.5,0.5,0.5) & (0.2,0.4,0.5) \\ (0.5,0.5,0.5) & (0.2,0.3,0.5) & (0.1,0.2,0.5) & (0.1,0.2,0.3) & (0.1,0.2,0.3) \\ (0.7,0.8,0.9) & (0.5,0.5,0.5) & (0.2,0.4,0.5) & (0.2,0.3,0.5) & (0.2,0.3,0.5) \\ (0.5,0.7,0.8) & (0.5,0.6,0.8) & (0.5,0.5,0.5) & (0.2,0.3,0.4) & (0.1,0.2,0.4) \end{bmatrix}$$

According to the FOWA operator, the new matrix is obtained as follows:

$$\widetilde{D} = (\widetilde{d_i})_{5\times 1} = \begin{bmatrix} (0.58, 0.68, 0.82) \\ (0.52, 0.62, 0.68) \\ (0.12, 0.22, 0.32) \\ (0.26, 0.38, 0.5) \\ (0.38, 0.54, 0.52) \end{bmatrix}$$

The expected value of d_i is decided using Equation (3). The ranking vector $\omega' = (0.327, 0.289, 0.078, 0.135, 0.171)^T$ is then obtained using Equation (4). Finally, the ranking of the alternative effects is No. 1, No. 2, No. 5, No. 4, and No. 3.

4.2.3. Effect Scheme Acquisition

The rotary effect is prioritized due to its high availability. Its engineering cases include the rotary tube machine gun, rotary worktable, electric bicycle, fast capping machine, and positioning punching device. It is known that the characteristic LT dimensions of the rotary tube machine gun are No. 16 (L^1T^{-1}), No. 25 (L^4T^{-4}), No. 27 (L^1T^0), and No. 37 (L^5T^{-4}). According to the case similarity, (1) they are converted into vector forms (0, −1), (3, −3), (5, −4), (3, 0), (0, −1), (1, −1), (3, −3), and (5, −4), in order. (2) The problem set is P = [1, $\sqrt{18}$, $\sqrt{41}$, 3], and the case set is C = [1, $\sqrt{2}$, $\sqrt{18}$, $\sqrt{41}$]. (3) The processed two new sets are P′ = [1, 0, $\sqrt{18}$, $\sqrt{41}$, 3] and C′ = [1, $\sqrt{2}$, $\sqrt{18}$, $\sqrt{41}$, 0]. (4) After substituting P′ and C′ into Equation (5), the similarity between the rotating tube machine gun and the target product is 0.91.

The characteristic LT dimensions of the rotary table are No. 11 (L^2T^{-4}), No. 16 (L^0T^{-1}), No. 27 (L^3T^{-3}), and No. 37 (L^5T^{-4}). The similarity with the target product is 0.80. Next, the characteristic LT dimensions of the electric bicycle are No. 25 (L^1T^{-1}), No. 27 (L^3T^{-3}), No. 35 (L^3T^{-2}), and No. 37 (L^5T^{-4}). The similarity with the target product is 0.82. The characteristic LT dimensions of the rapid capping machine are No. 11 (L^2T^{-4}), No. 16 (L^0T^{-1}), No. 27 (L^3T^{-3}), and No. 48 (L^3T^0). The similarity with the target product is only 0.48. The similarity of the remaining cases does not reach the pass line of 0.6, which is significantly different from that of the button battery ring device.

The function model of the rotary tube machine gun is shown on the left side of Figure 11. The elements reflecting the effect are circled by the dotted line box. After structural mapping, the conceptual scheme I is obtained: the feeding mechanism transports the shell to the predetermined position, and the rotating mechanism drives six buckle ring-striking devices to complete the buckle ring action in turn so as to realize the assembly link between the seal ring and the shell. The motor supplies energy for the rotating mechanism and feeding mechanism. A frame is used to support all the above components, as shown in Figure 12.

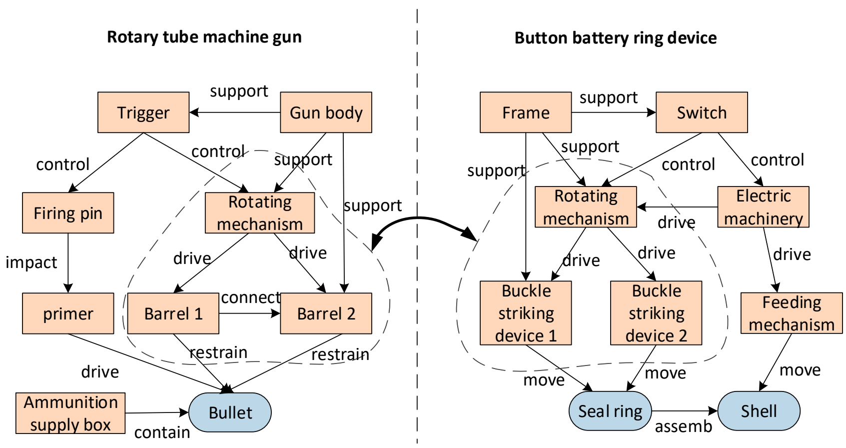


Figure 11. Analogy process of the rotating tube machine gun.

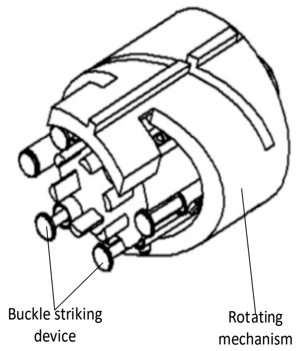


Figure 12. Scheme I.

The function model of the electric bicycle is shown on the left side of Figure 13. After structural mapping, conceptual scheme II is obtained. The motor drives the upper-toothed pulley to rotate through the transmission shaft so as to move the grooved conveyor belt. Unlike the general sprocket chain mechanism, which is only used to transmit power, the grooved conveyor belt in the ring buckle device can transport the sealing ring placed in the storage box, as shown in Figure 14.

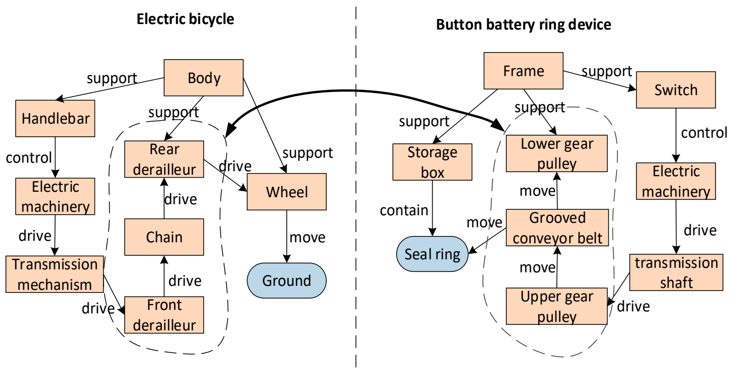


Figure 13. Analogy process of the electric bicycle.

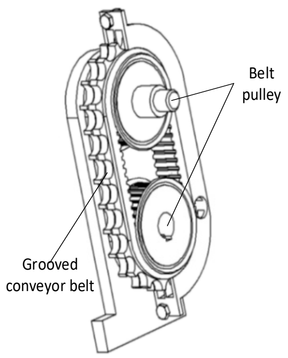


Figure 14. Scheme II.

The function model of the rotary table is shown on the left side of Figure 15. After structural mapping, conceptual scheme III is obtained, as shown in Figure 16. In the ring buckle device, the continuous rotation of the transmission shaft is converted into a one-way reciprocating motion of the movable guide rod by using the ratchet pawl mechanism. The reciprocating push rod is driven by the movable guide rod and constrained by the return spring at the same time so as to realize the continuous movement operation of the sealing ring.

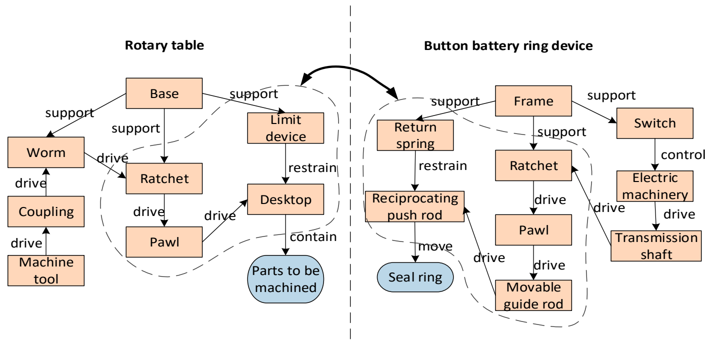


Figure 15. Analogy process of the rotary table.

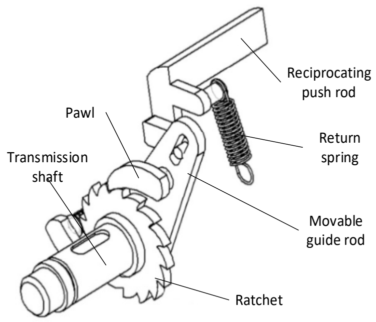


Figure 16. Scheme III.

In order to complete the button ring process and further improve the working efficiency of the device, the final scheme combines the respective advantages of the above three schemes. Redundant components are removed by trimming. The structure of the final scheme is shown in Figure 17, including a power transmission mechanism, a ring buckle striking mechanism, a frame, an intermittent driving mechanism, and an automatic feeding mechanism. The new scheme has the following features: (1) improving the buckle speed, reducing the buckle steps as much as possible, ensuring the continuity of the buckle action, and making the buckle speed reach 100 times/minute or even higher, as well as (2) improving the energy transmission and utilization efficiency, simplifying the action of buckle, reducing the number of moving parts in the process of buckle, improving the energy transmission efficiency, making a higher proportion of energy used for useful work, and reducing the use cost of equipment. (3) The structure of the ring buckle device is compact. By simplifying the action of the buckle movement, the number of elements of the execution subsystem is reduced as much as possible, making the structure of the execution subsystem compact and reducing the cost of the equipment. (4) The use of pneumatic or hydraulic components is reduced, the electro-hydraulic coupling system is also avoided, and the equipment control method is simplified to reduce the manufacturing cost of the equipment.

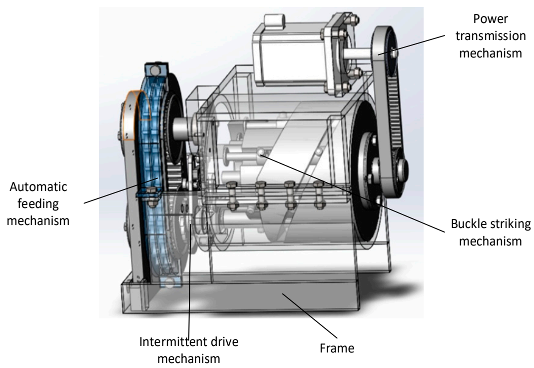


Figure 17. Final scheme structure.

5. Conclusions

This paper proposes a method of product improvement based on the knowledge mining and effect analogy. The length–time dimension is introduced to link the problem analysis and problem-solving. The method integrates the effect knowledge base construction, length–time dimension extraction, effect retrieval, effect ranking, analogy object selection, and effect structure mapping. The superiority and feasibility of the proposed method are verified by the comparative analysis of three effect retrieval methods and design improvement of a button battery ring device.

The research contributions of this paper are as follows: (1) The effect action principle is defined by introducing the C–K theory. The effect knowledge is abstractly expressed by using the ontology model. The effect retrieval is indexed by the proposed LT dimension, and the effect structure is mapped by introducing the analogy design, which improves the feasibility and necessity of the effect analogy and knowledge mining. (2) A method of product improvement is proposed using the knowledge mining and effect analogy. The LT-PES ontology model is used as the proposed method framework to obtain accurate LT dimensions. The triangular fuzzy number ranking method based on the FOWA operator forms a systematic effect retrieval mechanism. (3) The proposed method is described and verified in detail by two measures. First, the results of three effect retrieval methods on ten engineering cases are compared. The new method shows advantages in recall and precision. The other is the design of a button battery ring device, where three feasible effect structures are combined for design improvement.

This research also has certain limitations. The existing effect knowledge base is only a preliminary prototype. The number of retrieval samples is limited. In addition, the opinions of domain experts are used in the problem root cause analysis and effect results ranking. The expert experience can affect the final solution of effect structure mapping. Future work will develop computer-aided tools for problem analysis and solution acquisition to improve the adaptability and objectivity of the parameters in the model and minimize the negative impact of incomplete information on design results.

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