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Product Innovation Design Method Based on Scenario

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Abstract. The scenario can envision reasonable future states and effectively assist designers in finding innovation opportunities and getting valuable innovative product design solutions based on dynamic interactivity. However, there needed to be more systematic steps to express, reason, and solve scenarios in the innovation design domain. Based on this, a systematic approach to scenario-based innovation design is proposed in this paper. Firstly, the composition and logical expression of product scenarios are clarified, and then, a scenario element operation process based on the law of demand evolution is introduced to help construct diverse future scenario conditions. Secondly, a heuristic case search method based on effect retrieval and scenario element matching is introduced to obtain valuable innovative product design solutions adapted to new scenario conditions by analogy. Finally, the feasibility of the proposed method is illustrated with an innovative design case.

Keywords: Innovative design; Scenario element; Operation rules; Case retrieval.
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1 INTRODUCTION

As a symbol of the Industrial 4.0 era, the intellectual development of the manufacturing system promotes the new generation of leapfrog development of the manufacturing industry [36]. Innovative design, the foundation of intelligent manufacturing, causes R & D professionals to offer clients updated, more diversified, and humanized products [8].

Traditional demand-driven innovations, such as QFD-based methods [26,31], quantified the relationship between customer needs and engineering measures as a quality house and identified the essential measures to meet customer needs after data analysis and processing, thus guiding designers to seize the main contradictions and carry out a systematic approach to stability optimization design. Kano model-based model [15,32] captured the non-linear relationship between product performance and customer satisfaction by categorizing and prioritizing customer requirements and configuring product features. TRIZ-based method [9,28] provided a systematic set of innovation tools oriented to the problem of the invention. Ethnography [3,13] describes human activities in specific contexts through observational field studies and contextual interviews, providing valuable insights into the workflow and setup of system design. Nevertheless, these methods suffer from complex and time-consuming information acquisition, ambiguous processes, and no explicit expressions of customer wishes and demand attributes in their application [4]. In recent years, "scenario" which emphasize better thinking about the future from the present, have been introduced into the field of product design, which can assist designers in exploring a clear description of the hypothetical process of a product at a particular stage of its life cycle [2], exploring the most helpful innovation direction of the product from a future perspective, and significantly improving the logic and efficacy of innovative ideas.

Innovation comes from the exploration of uncertain environments [19]. The vision of the scenario involving "identifying the behavior of new users and finding out how they create a unique future [7]" is consistent with the future-oriented practice of product innovation design. Some scholars believe that innovation originates from transforming concept space and mapping different knowledge systems. The core is transforming knowledge from one scenario to another [11]. Product design is a scenario analogy process to meet function requirements [10]. By constructing scenarios, future development can be predicted to help make correct decisions and responses [16]. The scenario's forward-looking, interactive, and uncertainty-based characteristics can help designers quickly and accurately find future application prospects and get valuable innovative design solutions.

Scholars have introduced scenarios into the product innovative design process, as shown in Table 1. The above research expands the application of scenarios in innovative design, but the theory is not yet mature. For example, the description of scenarios was not standardized [24], the reasoning process was unclear [17], and the overall process was complex and abstract.

Scholars	Scientific contribution	Critically evaluation
Randt [21]	The scholar obtained the expectation of future user demand under uncertainty by considering the choice of future scenarios to derive robust design requirements, and a case study on aircraft design was used to demonstrate the method's validity.	The principles for supporting customer-oriented thinking was put forward, but the specific rules for conducting scenario variable were not mentioned.
Suri and Marsh [29]	They proposed a method for discovering product innovation opportunities by constructing scenario stories and sketches.	The method discovered the innovation space of products from human differences, ignoring the influence of environment-related factors.
Anggreeni et al [1]	They proposed a product design process based on human-computer interaction and scenario inspiration.	The scenario representation and inspiration mainly rely on stories and diagrams under empirical thinking and lack a logical reasoning process.
Shin et al [27]	They developed a suggestion tool for scenario generation to obtain user requirements by finding scenario variants.	The macro factors, such as economy and policies, were mainly considered, with less attention paid to stakeholders and specific environmental conditions.
Zhang et al [34]	They proposed a product design process in which environmental profile transformation guides scenario analysis.	No specific steps were mentioned to get the solution through environment variables.
Lee et al	They proposed an approach using cross-	There was a lack of selection strategy

[18]	impact analysis and an analytical hierarchy process for a scenario-based roadmap.	for future impact factors of products.
Hussain et al [14]	They suggested a method of technology foresight by combining scenario planning and technology roadmap.	The method has been applied to only one case with particular contextual characteristics.
Liu et al [20]	They applied scenario analysis to the product reconfiguration design and obtained potential functional units by analyzing the internal system and external scenario.	The process of solving innovative problem-oriented solutions has certain limitations.

Table 1: Relevant research studies on scenario in product design

This paper explores a new approach to introducing scenarios into product innovation design. First, a scenario knowledge representation is proposed, then scenario operation rules guided by requirement evolution laws are introduced to construct new scenario conditions. To better utilize innovation opportunities to obtain innovation solutions, an effect search process and a heuristic case-by-case search method are proposed by matching effect and scenario elements, which are used to obtain valuable innovative product design solutions adapted to new scenario conditions by analogy. Finally, a scenario-based innovative design process is proposed. The proposed method is verified by an innovative design of the Chinese medicinal materials (CMMs) dispensing machine.

2 PROPOSED METHOD

2.1 Product Scenario Knowledge and Representation

The purpose of knowledge representation is to logically represent the corresponding knowledge in a practical expression and structure for flexible access by users. The rational representation of product scenarios is this project's starting point and basis. However, scenarios are usually described in narrative format, and the basic logic is unclear [4] in the existing studies. The concept and composition of product scenarios were clarified, and the relationship between product action processes and scenarios as specified in this section. Product scenario knowledge is characterized by extracting vital elements in the evolution of the product scenario and labeling their logical relationships.

2.1.1 Composition of product scenario

The product scenario can be viewed as the development from the initial scenario state (IS) to the expected final scenario state (ES) under the product action.

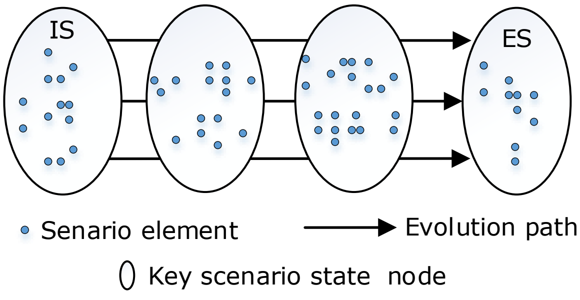

Figure 1: Product scenario evolution process.

In a product action cycle, the product scenario begins in the initial state, which contains a series of necessary scenario elements making up the initial scenario node, and as the product action acts, the scenario evolves into another key state node, which is the stage completion of some functional action. At the same time, the key scenario elements in this node also change, and with the advancement of a series of scenario nodes, the final product action is completed, and the expected final scenario state containing the required scenario elements is reached, as shown in Figure 1.

The objective things and their states that play a key role in the evolution of the key scenario state node are called scenario elements (*E*), in which the scenario state is simplified as the set of scenario elements. Referring to the expression method of elements in Extenics [33], the scenario element *E* is characterized as

$$E=(N,C_n,V_n)$$

Where *N* represents the concept name of the scenario element; C_n represents the nth feature of the scenario element; V_n denotes the state index of the nth feature.

Due to the interaction of users, products, and the environment, the product scenario evolves according to the objective law to complete the established function. Therefore, product scenario elements can also be divided into three categories: product-related elements (*Ep*), user-related elements (*Eu*), and environment-related elements (*Ee*). In the scenario, this type of scenario element that marks the completion of the main design purpose is called the core scenario element, which can be recorded as Ec. For example, the core scenario element of the vacuum cleaner is dust, and the successful scenario of its work must meet the expected changes in the location of the dust.

The scenario condition is the initial state of the product scenario without the product's existence and reflects the initial state of the product application. The set of scenario conditions where the product is introduced and the scenario evolves to obtain the desired result is called the scenario boundary of the product, which reflects the workable working range of the product.

2.1.2 *Representation of scenario behavior process*

The evolution process of a product scenario is that the relevant scenario elements interact with each other in a particular temporal order in an orderly manner so that the scenario evolves from the initial state to the expected final state.

To express the scene evolution process intuitively, a scenario behavior chain construction method is proposed. A typical work scenario and an action cycle of the product are used as objects based on the change of the scenario state after a particular role is completed. The external interaction behavior EB and internal inter-agency operation behavior IE of the expected product scenario in a typical work cycle are analyzed, and the scenario behavior chain is constructed according to the causal sequence, as shown in Figure 2.

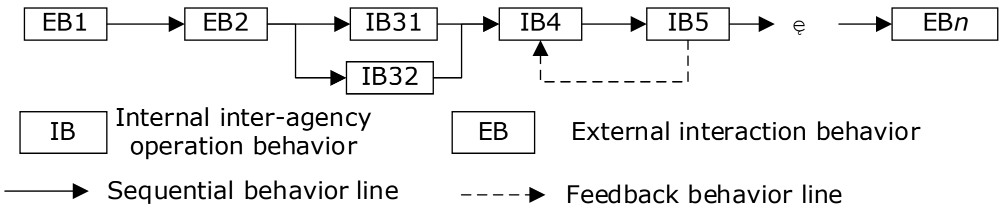

Figure 2: Scenario behavior chain of product action.

Each scenario behavior has corresponding pre-order and post-order key scenario elements. When the pre-order elements have complete key characteristics, the scenario behavior can trigger the corresponding evolution.

2.2 Exploring New Scenario Conditions

The product's characteristics are derived from the scenarios in which the product acts, and its functional requirements are closely related to the scenario conditions in which they occur [1]. Several typical possible future scenario conditions are constructed by exploring the key influencing factors in the product scenario conditions. The product should be able to drive these possible scenario conditions to the expected final scenario state. By analyzing the product's interactivity in actual situations, the possible characteristics of the future product can be inferred, and innovation opportunities can be obtained. A reasonable exploration process of product scenario conditions is proposed in this section.

2.2.1 Scenario element operation rules

The discovery of new scenario elements is the key to exploring scenario conditions. Through the operation of the original scenario elements, reliable and valuable scenario conditions can be provided for designers. The basic scenario element is set as E_a=[N_a, C_a, V_a], and the following five scenario element operation rules are summarized in Table 2.

Operation rules	Resume	Operation process	Remarks
Rule1	Expansion of multiple features of the same type of an element	$Ea \Rightarrow E_a = \begin{bmatrix} N_a, & C_a, & V_a \\ & C_b, & V_b \\ & \cdots & \cdots \end{bmatrix}$	Remark 1: There is a correlation function between C_a and C_b or/and V_a and V_b. Or there is an inclusion relationship between E_a and E_b .
Rule2	Convert to an element with the same characteristics	$E_a \Rightarrow E_b$=[N_b, C_a, V_a]	
Rule3	Reset status indicators of the element	$E_a \Rightarrow E_b$=[N_b, C_a, V_a]	
Rule4	Convert to a scenario element with relevant characteristics	$E_a \Rightarrow E_b$=[N_b, C_a, V_a] (Remark 1)	
Rule5	Delete or add elements	$E_a \Rightarrow E_b$=[N_b, C_a, V_a]	

Table 2: Operation rules of scenario elements.

2.2.2 Mapping process of scenario element operation

The construction of product scenario conditions is a discovery of future environmental elements, human factors, and core scenario elements and is an exploration process oriented to valuable needs. Therefore, it is possible to combine the operation of scenario elements with the laws of demand evolution. TRIZ summarized five laws of demand evolution [30] and the characteristics of the corresponding demand, as shown in Table 3.

Laws of demand evolution	Characteristics
Law1: Idealization of demand evolution	C1.1 Improve quality
	C1.2 Reduce production time
	C1.3 Reduce side effects
Law2: Dynamic of demand evolution	C2.1 Increase adaptability
	C2.2 Reduce manpower
Law3: Coordination of demand evolution	C3.1 Improve coordination
	C3.2 Easy operation
Law4: Integration of demand evolution	C4 multifunction
Law5: Specialization of demand evolution	C5 Improve pertinence

Table 3: Laws of demand evolution and characteristics of demand evolution.

An effective relationship between the scenario and demand evolution law is established to obtain valuable design demands through operation strategies of scenario elements. The process is as follows.

The operational scenario elements Ea= [Nax, Tax, Vax] → is linked to C (from 1.1 to 5) → is linked to Rule (from 1 to 5)

The operational mapping process is summarized as shown in Figure 3.

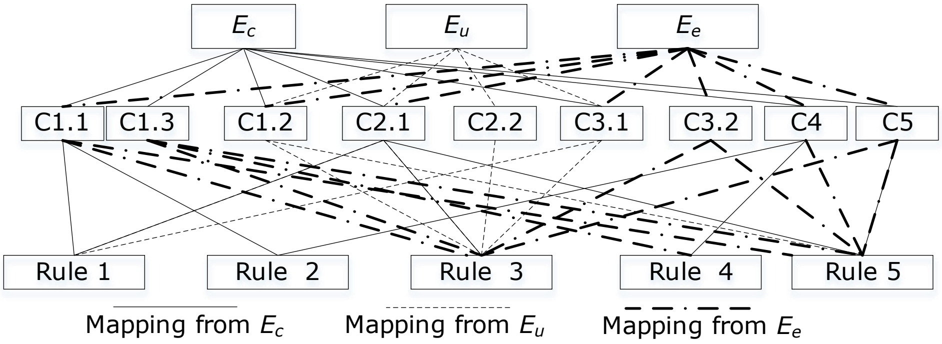

Figure 3: Mapping process of scenario element operation based on demand evolution law.

2.2.3 Construction of future scenario conditions

Referring to the intuitionistic logic school in scenario planning [6] and according to the characteristics of engineering design, the following methods for constructing the future scenario conditions of products are formed.

1) Set up the initial scene: The typical actual scenario of the prototype product is token as the initial scene and the scenario element information is extracted. The core scenario elements of the prototype product, the main features, and key characteristics are clarified. The extraction of user-related elements should be considered in terms of age, gender, language, and behavior habits. For environment-related elements, the analysis and extraction of relevant resources can be carried out by gradually narrowing down the environment. To avoid omissions, the resource analysis strategy in TRIZ [24] is referred to for finding and extracting, as shown in Figure 4.

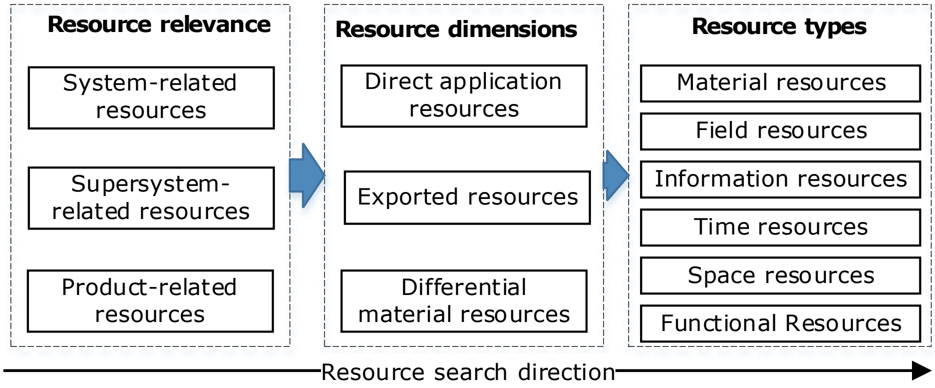

Figure 4: Strategy for resource search.

2) Identify key drivers and perform scenario operations: Analyze existing meanings of scenario elements and select appropriate operation directions and rules based on the mapping process. Apply the selected rules and consider the future application potential of the product to discover new scenario elements. The core scenario elements consider variability and introduce relevant features or indicators. Environment-related elements need to consider features that have corresponding restrictions or provide the necessary convenience, or introduce inherent features that differ from the location of the scenario boundaries. User-related elements consider group feature indicators to reset or extend joint features.

3) Construct plausible scenario conditions: Reorganize new scenario elements to obtain potential future scenario conditions, which should satisfy the following four points: Compatibility requires that the combination of scene elements does not create interference. Rationality requires that the combined key scenario elements can be realized in the same scenario and are consistent with common sense. Novelty requires that the combined scenario conditions exceed the scenario boundaries of the product. Development potential requires that the new scenario conditions have application value.

2.3 Scenario-oriented Case Retrieval

The product is a dependent variable based on the completeness and consistency of change in scenario conditions and evolution. The scenario variables in the new scenario conditions are brought into the units of the original scenario behavior, which leads to abnormal evolution. To complete the intended scenario, the product design solution needs to be reconstructed, and the design by the analogy of cases is efficient and fast. An analogous case discovery process is the key to this part, and a scenario-oriented case retrieval process is proposed, as shown in Figure 5.

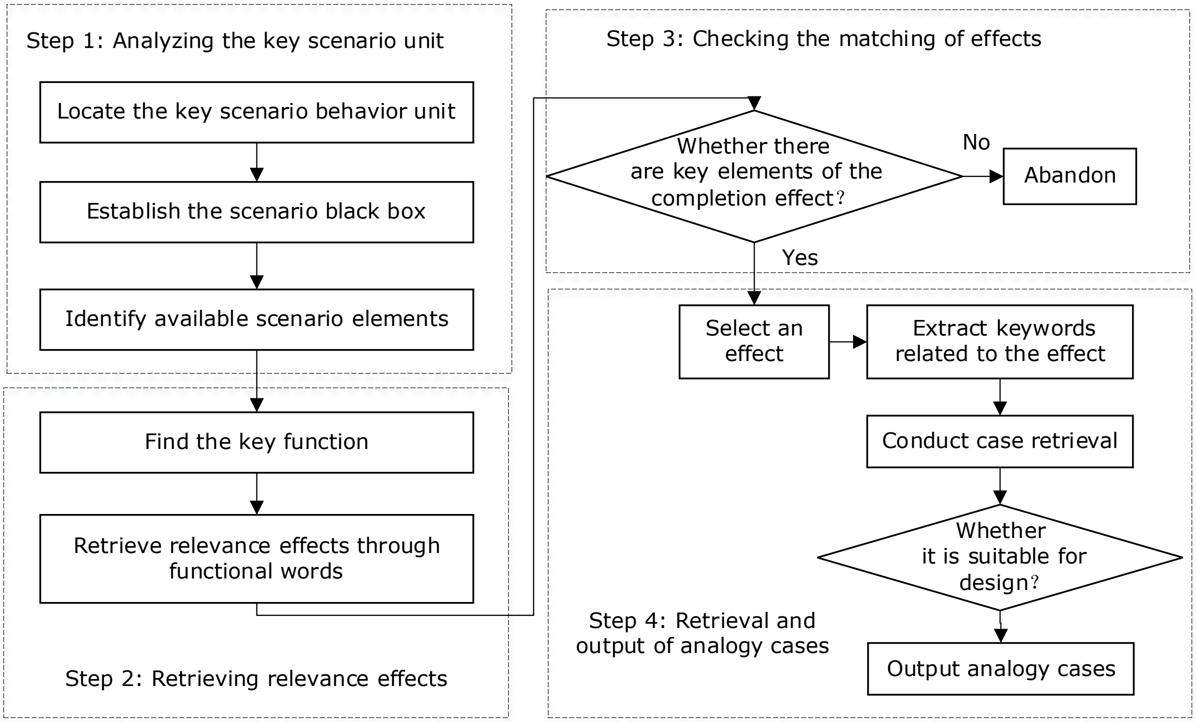

Figure 5: Scenario-oriented case retrieval process.

Step 1: Analyzing the key scenario unit

To locate scenario behavior units that cannot work correctly, new scenario conditions are brought into the original behavior chain of the prototype product. The scenario black box of the unit can be established, and clarify the pre-order and post-order scenario elements can be identified. Then other scenario elements expected to be available in the scenario are obtained.

Step 2: Retrieving relevance effects

The characteristic changes of key scenario elements in the scenario unit are analyzed, and a causal analysis [30] is used to find the key function that supports the evolution of the scenario behavior. Then taking the identified function as the keyword to retrieve the relevance effect. This process can be implemented by introducing the effect retrieval database or CAI software.

Step 3: Checking the matching of effects

It is necessary to determine whether the known scenario elements satisfy the completeness of the effect conditions with the following judgment rules.

1) The expected pre-order scenario element contains the features at the input of the effect or can be got by a simple transformation; if flow containing this feature exists or can be output in the surrounding environment or the previous scenario behavior, it will also be considered as a match.

2) The output side of the effect can mention the required characteristics of the expected post-order scenario element either directly or after a simple transformation.

Step 4: Retrieval and output of analogy cases

After selecting the appropriate effect, the relevant case needs to be searched. The key to the search is the selection of search terms. Since the name of the effect rarely appears in the patent text or product descriptions, it needs to be converted into common key behaviors, expressions, institutions, etc. Keywords for effects can be converted into a series of functionally relevant verbs based on the behavior of the case application. For example, for the Venturi effect, the designer could first associate the vacuum cleaner with the desired "move" function and extract from the behavior of the vacuum cleaner the keywords related to the behavior "air suction", "suction ", "absorption", etc.

Based on the keywords extracted from the desired functions and effects, search formulas such as "function keywords and/or effect keywords" are constructed to be brought into the corresponding patent database or other case search libraries for patent or related product searches.

For the retrieved cases, the structure of the new scenario behavior required for its implementation is further extracted, and the designer selects a suitable case as an analogous source considering the structure complexity, matching, improvement difficulty, cost, etc.

The process of scenario-based case search takes scenarios as clues and draws on designer experience induction while introducing CAI and patent search analysis software to balance the relationship between innovation dispersion and repeatability. Future research will be conducted on the whole process software.

3 SCENARIO-BASED INNOVATION DESIGN PROCESS

The scenario has unique advantages in the stage of innovation opportunity discovery [5], and case analogy design can help designers quickly get the design scheme [12]. Therefore, this study proposes a scenario-based innovation design process, as shown in Figure 6, which comprises five steps.

Step 1: Extracting initial design information

Identify known elements of the future product solution based on design tasks, typically including some key initial and end solution elements, and articulate key elements, key feature attributes, and feature state changes.

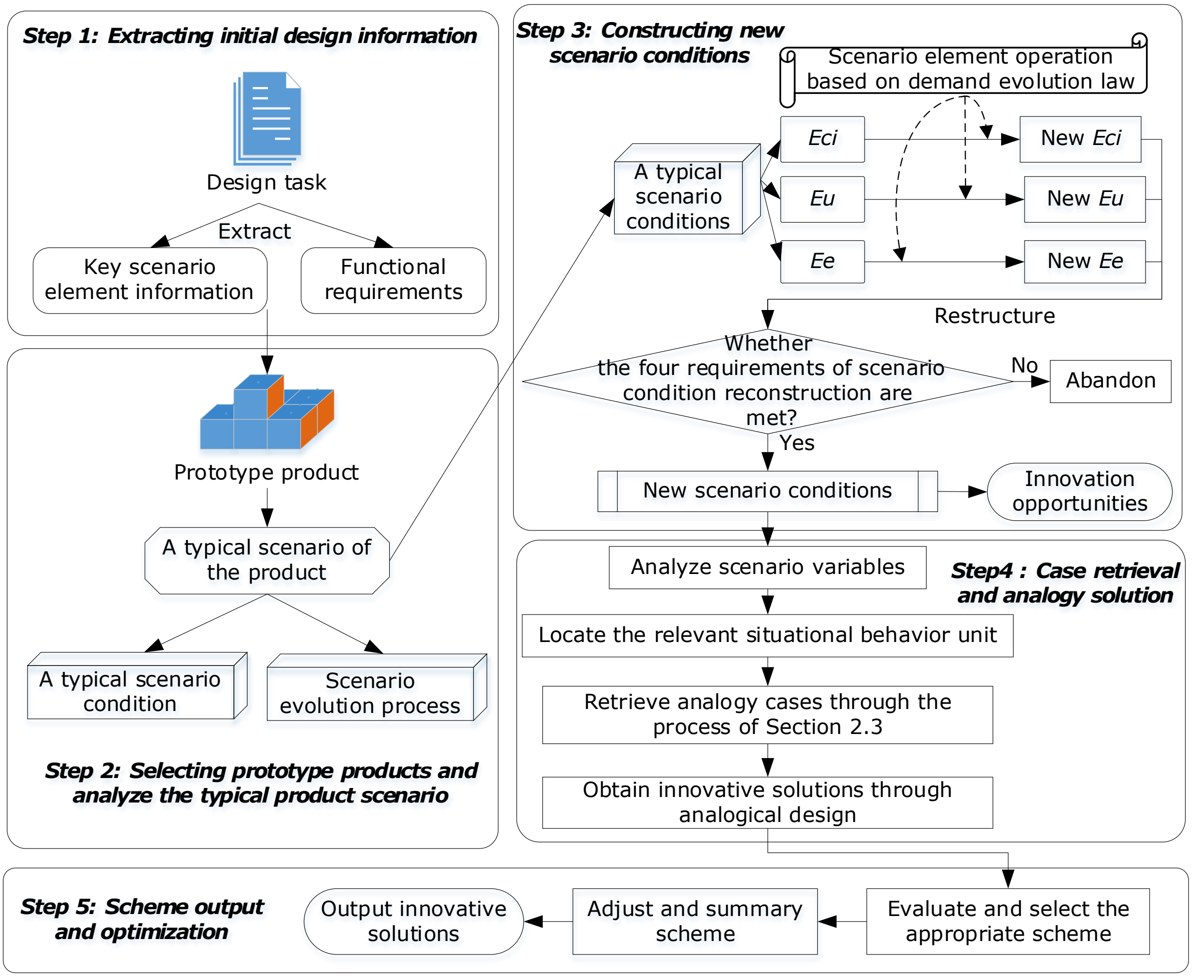

Figure 6: The process model of product innovation design based on the scenario.

Step 2: Selecting prototype products and analyze the typical product scenario

Based on the design requirements, the existing typical products are selected as prototypes through market research or patent search, and product scenario analysis is performed to obtain information on typical scenario conditions and the scenario evolution process.

Step 3: Constructing new scenario conditions and identifying innovation opportunities

According to the process described in Section 2.2, based on the key scenario elements of the prototype product, the key scenario elements that may exist in the future product scenario can be obtained through the scenario element operation mapping process. Then the potential scenario conditions in the future can be obtained by restructuring relevant elements. It requires that products need to adapt to new scenario conditions, thus generating new innovation opportunities.

For example, a scenario expansion analysis was performed for a mine track vehicle. Choosing to evolve the environment-related elements to C4 multifunctional, applying Rule5 to add possible associated environment elements N_1Ee= [track, static geometry state, unknown] or N_2Ee= [mine air, gas concentration, unknown], the new scenario condition can add N_1Ee or N_2Ee, which can be further inspired to add a track static geometry state detection function or a gas concentration detection function for the mine track.

Step 4: Case retrieval and analogy solution

The scenario variables are brought into the original scenario behavior chain for analysis, and the associated scenario behavior units are located. Then the appropriate analogy cases can be retrieved by applying the process in Section 2.3.

In the analogy design, it is necessary to replace or add relevant structures to the association behavior and make adjustments according to the mechanical principle. If there is a conflict problem, the TRIZ tool should be introduced to solve it.

Step 5: Scheme output and optimization

It is also important to evaluate the schemes. A method based on value engineering [22] is proposed as follows.

$$V_i = F_i / C_i \tag{3.1}$$

where V_i is the coefficient value of scheme i, F_i is the function benefit score of scheme i. C_i is the cost coefficient of scheme i.

Calculating the Fi using Equation (2.2) and Equation (2.3):

$$F_i = \alpha_i \bullet F_0,\ \alpha_i = \sum_{j=1}^{n} W_j \times k_{ij} \tag{3.2}$$

$$C_i = \beta_i / C_0 \tag{3.3}$$

Where F_0 and C_0 respectively represent the functional benefit score, and cost score of the benchmark scheme; α_i represents the comparison coefficient of F_i and F_0; β_i is the comparison coefficient of C_i and C_0; W_i represents the comparison coefficient of the ith evaluation index; K_{ij} represents the relative value coefficient of the ith scheme relative to the benchmark scheme in the jth evaluation index; C_i represents the comparative cost coefficient of C_0. The prototype scheme is regarded as the benchmark scheme.

The evaluation indicators are obtained through expert discussion, and the key indicators are expressed as M={M1, M2,..., Mn}. M may include performance indicators, functional indicators, enterprise strategy-related indicators, etc. C represents the comprehensive cost of the product.

According to the evaluation results, the priority of the scheme application is determined. Based on the solution sought, the product's new structure is established. Technical details are clarified to optimize the design. Finally, the innovative scheme meeting the design requirements can be output.

Design is a collaborative process, and some steps of the proposed approach require collaboration among designers, e.g., members of the design team can follow the steps to discover new scenario elements separately and discuss and filter the appropriate combination of scenario conditions. The steps of case retrieval and analogy generation can be made easier and avoid individual thinking by dividing the work and discussion among members.

4 CASE STUDY

Traditional Chinese medicine (TCM) plays an important role in ensuring people's health. In the process of diagnosis and treatment of TCM, the accurate configuration of Chinese medicinal materials（CMMs）is the key to ensuring efficacy. It is the key to ensuring the efficacy of treatment [25]. However, there are some problems in the process of CMMs dispensing, such as low efficiency, inaccurate weighing, and high workload. The development of an automatic CMMs dispensing machine is of great significance.

4.1 Extracting Initial Design Information

After analyzing the product design task, the dominant demand is "dispensing CMMs", the main body of the scenario element is "CMMs", The key features are "position" and "weight", the change of feature state is from "medicine box" to "pharmaceutical bag" and from " not measured" to " the stated dose" respectively. The core scenario elements extracted from the design task are

$$Eci = \begin{bmatrix} CMMs, & Position, & Medicine\ box \\ & Weight, & Not\ measured \end{bmatrix}; Ece = \begin{bmatrix} CMMs, & Position, & Pharmaceutical\ bag \\ & Weight, & The\ stated\ dose \end{bmatrix}$$

4.2 Selecting Prototype Products and Analyzing the Typical Product Scenario

After analyzing related patents and devices, an automatic CMMs dispensing device was selected as a prototype, as shown in Figure 7. The equipment relies on manually adding the required CMMs to the equipment. After starting, the CMMs are vibrated out of the medicine hopper and fall into the medicine feeding mechanism due to gravity, and the vibrator is controlled to start and stop according to the feedback from the load cell to the control system, while the motor in the medicine feeding mechanism is controlled to drive the front baffle to open and close so that the exact weight of the CMMs fall down and complete the medicine dispensing work.

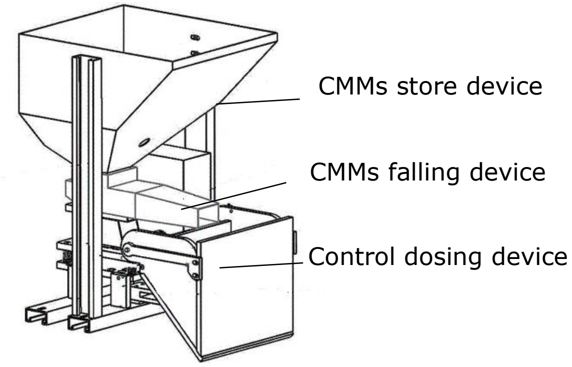

Figure 7: A vibrating blanking type CMMs dispensing equipment.

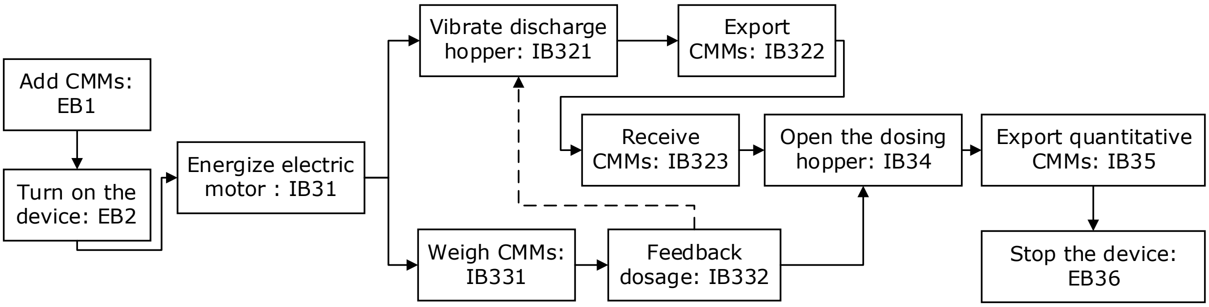

Figure 8: The scenario behavior chain of the prototype product.

The typical action place of the prototype product is indoors, such as in pharmacies, hospitals, etc. In the expected scenario evolution, the initial scenario conditions include P_0Ec_1= [*CMMs*, Physical shape, *Small and regular granules*], P_0Ee_1= [*Indoor*, *State*, *Normal temperature and pressure*],

P_0Ee_2= [*Socket*, *State*, *Presence of electricity*], P_0Eu_1= [*Users*, *Characteristics*, *The able-bodied*]. The scenario behavior chain of the prototype product is shown in Figure 8.

4.3 Constructing New Scenario Conditions

With the scenario condition elements of the prototype product as a reference, possible scenario elements in the future scenario conditions of the product are explored:

Ec can be selected for operation. The prototype product can only be configured with relatively small and regular granular CMMs. If it evolves in the direction of C2.1 Increase adaptability, P_1Ec_1= [*CMMs*, *Physical shape*, *Granular and powdered*] can be obtained by applying Rule1 operation. If it evolves to C1.2 Reduce production time, Rule5 is used to add the dose information display to obtain the new scenario element P_2Ece_1 = [*CMMs*, *status, quantitative continuous multiple bags*].

Ee can be selected for operation, P_3Ee_2 can evolve towards C2.1 Increase applicability, and Rlue5 operation can be applied to delete power socket P_0Ee_2.

Similarly, a series of new scenario elements such as P_4Eu_1= [*user*, *ingredient*, *Chinese medicine trader*], P_5Eu_2= [*user*, *degree of participation*, *little or no*], P_6Ec_1= [*Western medicine*, *Physical shape*, *Tablet*], P_7Ee_1= [*wholesale herb market*, characteristics, l*arge space and a large amount of medicine required*] can also be obtained through similar steps.

Based on the obtained scenario variables, a distribution of possible future scenario variables can be shown in Table 4.

Types of scenario elements	Key scenario elements	Environment-related elements	User-related elements
Possible future scenario elements	P_0Ec_1= [*CMMs*, *Physical shape*, *Small and regular granules*]	P_0Ee_1= [*Indoor*, *State*, *Normal temperature and pressure*]	P_0Eu_1= [*Users*, *Characteristics*, *The able-bodied*]
	P_1Ec_1= [*CMMs*, *Physical shape*, *Granular and powdered*]	P_0Ee_2= [*Socket*, *State*, *Presence of electricity*]	P_4Eu_1= [*user*, *ingredient*, *Chinese medicine trader*]
	P_2Ece_1 = [*CMMs*, *status*, *quantitative continuous multiple bags*]	Delete P_0Ee_2	P_5Eu_2= [*user*, *degree of participation*, *little or no*]
	P_6Ec_1= [*Western medicine*, *Physical shape*, *Tablet*]	P_7Ree_1=[*wholesale herb market*, *characteristics*, *large space and large amount of medicine required*]	

Table 4: Distribution of possible future scenario variables.

According to the new scenario variables and the original scenario elements, multiple new scenario conditions can be reconstructed. For example, P_1Ec_1 + *P2Ece*$_1$ +original scenario elements mean the powder or granular CMMs can be quantitatively configured several times in succession. P_3Ee_2 + P_6Ec_1+original scenario elements mean the equipment shall be able to be configured with CMMs granules and western medicine tablets and can operate without an external power supply. Since the first scenario condition has a broader application prospect and the related technology is still immature, it can be prioritized as a case for further design, and other scenario conditions can also be selected for further design as needed.

4.4 Case Retrieval and Analogy Solution

The strong relevant behavior of P_1Ec_1 is "IB322: Export CMMs" by introducing P_1Ec_1 into the scenario behavior chain. The key function action of IB322 can be abstracted as "move solid"; there are also air, gravity, electricity, rotary power, and other resources in the scenario. The pre-order scenario elements of IB322 are [*CMMs*, *location*, *medicine box*], [*energy*, *type*, *kinetic energy and electric energy*], and the post-order scenario elements are [*CMMs*, *state*, *falling*], [*energy*, *type*, *kinetic energy and electric energy*]. There are also air, pressure, gravity, electricity, rotary power, and other resources in the scenario.

A knowledge base called "effect knowledge base for function realization of different forms of matter" [27] is used to search for available effects: vibration, gravity, Pascal's law, Bernoulli effect, spiral principle, etc.

Due to the existence of pressure and air, the Pascal's effect can be selected, such as "air suction" and "negative pressure" can be extracted as the key word from the Pascal's effect, main function can be abstract as" move object". Then, With ("air suction" and "move object") as the search formula brought into the Patsnap patent database for patent search, a series of patents related to "suction moving object" were matched, and after preliminary screening, over 50 patents were obtained, including "A kind of negative pressure red dates picking machine (ZL201520865758.1)" and "A seed nut negative quantitative pressure self-priming loading device (ZL201920112642.9)". Further, a case with a high degree of matching with the expected scenario was selected and determined, as shown in Figure 9(a), then an innovation scheme 1 can be got through analogy improvement, as shown in Figure 9(b).

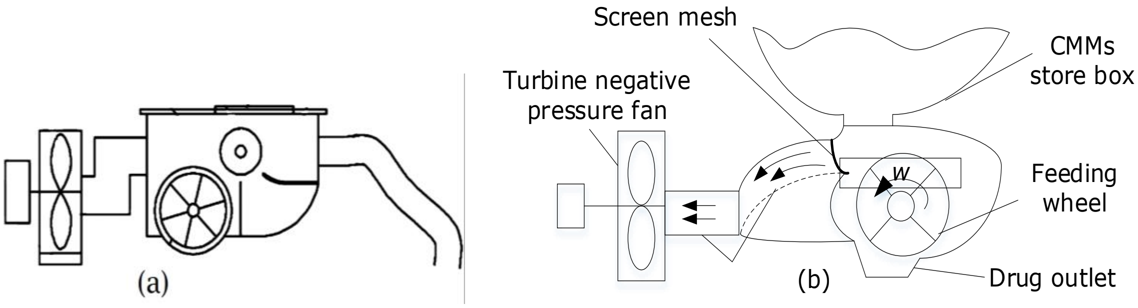

Figure 9: (a) Schematic diagram of the negative pressure red dates picking machine, (b) Schematic diagram of the negative pressure type CMMs transport mechanism.

Similarly, by selecting the spiral principle, keywords such as "rotate" and "spiral" can be extracted, then, combined with functional keywords, a series of search formulas can be reorganized, for example ("rotate" and "move object") as a search term applied to Patsnap patent database to search for relevant patents, More than 40 patents such as "Plate glass grading and feeding device(ZL202223093963.X)" and "A high-efficiency screw conveyor screening device (ZL202220301488.1）" were granted. Through manual sifting, a reference solution with a simpler structure and meeting the design requirements was obtained, as shown in Figure 10(a). Using it as a reference and combining it with the expected scenario evolution approach for analogous design, a new solution called scheme 2 is shown in Figure 10(b).

4.5 Scheme Output and Optimization

After expert analysis, the following key evaluation indicators M= {speed, accuracy, complexity, reliability, novelty, applicability}, weight assignment w=$(0.16, 0.18, 0.15, 0.2, 0.16, 0.15)^T$ are determined. A relative assignment is obtained by comparison with benchmark technology, as shown in Table 5.

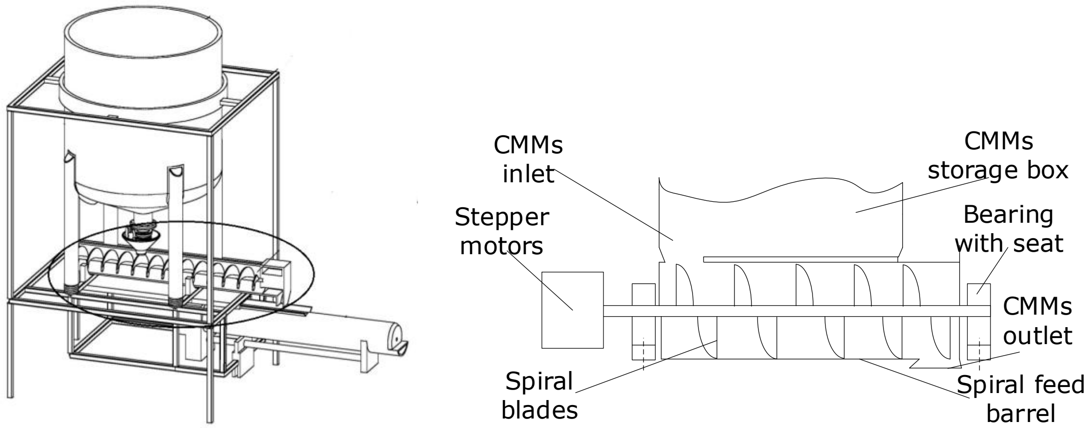

Figure 10: (a) Schematic diagram of Plate glass grading and feeding device, (b) Schematic diagram of the screw feeding type CMMs transport mechanism.

Indicators Schemes	Speed	Accuracy	Complexity	Reliability	Novelty	Applicability	Cost
Benchmark	1	1	1	1	1	1	C_0
Scheme 1	2.1	1.2	0.8	1.1	2.1	1.2	$1.2C_0$
Scheme 2	2.3	1.3	1.4	1.2	1.8	1.8	$1.1C_0$

Table 5: Evaluation and assignment of schemes.

Taking the assignment value into formula (3.1)~(3.3). After calculation, $V_0=F_0/C_0$, $V_1=1.17\ F_0/C_0$, $V2=1.46\ F_0/C_0$. Due to $V_2>V_1>V_0$, scheme 2 has higher advantages, which can be used as the preferred design, and scheme 1 as an alternative. In the same way, an innovative scheme design of continuous weighing and collecting device is obtained by scenario variable P_2Ece_1 as shown in Figure 12.

Through the above analysis, the solution of the technical solution is obtained, and the technical system is further analyzed and reconstructed to build a functional model, as shown in Figure 11.

By integrating and optimizing the scheme shown in Figure 12, a new CMMs dispensing equipment can be obtained. The main working principle is as follows: After the device is started, the CMMs in the CMMs storage box fall into the spiral feeding device due to gravity and move forward driven by the downward rotating Archimedes spiral rod driven by a stepper motor and fall from the outlet to the small compartment of the continuous feeding device. The device can be started, stopped, and cycled according to sensor control.

To verify the feasibility of the scheme, the innovative CMMs equipment was applied to dispensing CMMs, such as licorice, cassia seed, angelica dahurica, etc. Experiments have proven that the equipment has the following advantages:

(1) The equipment mainly relies on the screw feeding mechanism based on the principle of the spiral effect to complete the quantitative delivery of Chinese medicine, which ensures the stability and accuracy of CMMs delivery.

(2) The equipment has a high degree of automation and can continuously output and dispense multiple portions of CMMs according to the input quantity information so that multiple portions of CMMs can be configured at one time, which greatly enhances the configuration efficiency of CMMs.

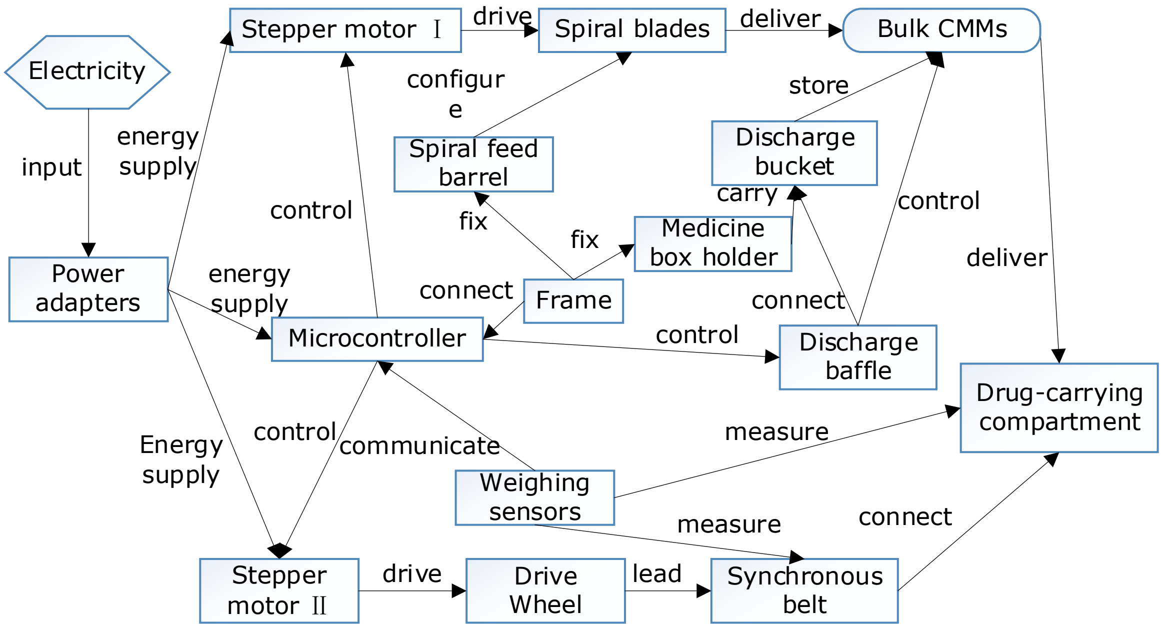

Figure 11: Functional model of the new scheme.

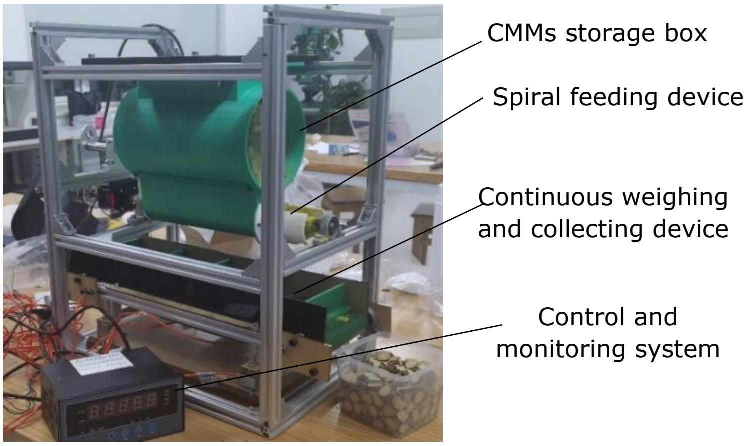

Figure 12: Physical prototype of the new CMMs dispensing machine

(3) The equipment can configure the most commonly used types of CMMs in Chinese medicine pharmacies, such as powder, roots, and granules, and control the stepper motor and other high-precision components according to the accurate feedback of the load cell information, which makes the dosage configuration more accurate and within the allowable error range of the pharmacopeia.

5 METHOD EVALUATION AND DISCUSSION

To evaluate the proposed method, our method was compared with four existing methods. Twenty-five master's degree students with the same engineering background were organized and divided into five groups equally to be proficient in QFD-based method, Kano model-based method, TRIZ-based method, ethnography, and Proposed method, respectively. The innovative design was carried out within 5 hours based on the same case conditions in section 4 and the corresponding result indicators, as shown in Figure 13, which shows that the proposed method has some advantages in terms of innovation opportunities and innovative solutions output.

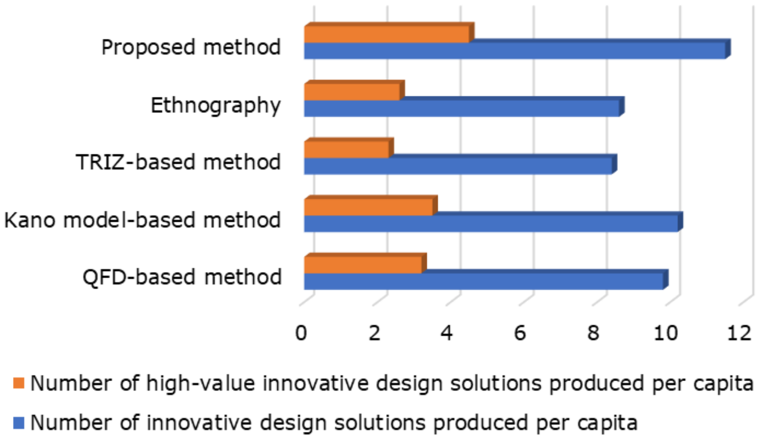

Figure 13: Results of the five-method controlled test.

Two professors, two senior engineers, and two junior engineers, meanwhile, were invited to supervise the above-controlled experiments throughout, rating the applicability, quantity, novelty, and commercialization of the innovations produced using the different methods using an evaluation scale from 1 (worst) to 6 (best), based on the experimental process and results, combined with their own design experience. The average scores for all five methods are presented in Table 6. In conclusion, the proposed method has the highest overall score and can help designers to obtain high-quality innovative design solutions more effectively.

Design methods	Applicability	The innovative result			Total score
		Number	Novelty	Commercialization	
QFD-based method	4.50	2.50	2.17	2.33	11.50
Kano model-based method	4.17	3.50	3.17	3.00	13.83
TRIZ-based method	3.83	3.50	3.00	3.33	13.67
Ethnography	2.67	2.17	2.33	2.33	9.50
Proposed method	4.00	3.50	3.83	3.33	14.67

Table 6: Average scores of reviewed methods.

The characteristics of the above methods have been summarized: QFD-based method can transform customer and market demands into relevant technical requirements, but the acquisition of requirements relies on market research and designers' subjective experience and pays less attention to novel requirements. Kano model-based method provides a method for ranking product requirements, but there are problems, such as weak preliminary requirements and complicated data processing. TRIZ-based method provides analytical tools and solutions for identifying invention problems and is good at finding innovative solutions through problems, but is more macro abstract for the acquisition of requirements. The ethnographic approach focuses on the impact of human variability on design, but the field survey approach is more time-consuming and lacks the process of converting research results into design guidance. In the meantime, these methods mainly focus on the needs and solutions of the present node and lack expectations for the variable future. Our proposed method introduces scenarios to quickly obtain the future needs of users by anticipating the dynamic future, which ensures the novelty and diversity of the design, the interactivity of the scenarios ensures the practicality of the innovation, and the systematic reasoning steps and processes facilitate the application by designers.

6 CONCLUSIONS

The scenario gives designers a future-oriented perspective to get innovative design solutions by adapting product requirements and functional structures to future changes. A systematic scenario-based product innovation design approach was proposed in this paper. To solve the shortcomings of the existing scenario descriptions which are not logical, a formal representation of product scenarios based on key scenario elements was proposed by clarifying the basic composition of product scenarios. The modeling method of the product scenario evolution process is also given to facilitate designers to visualize the expected dynamic mode of action and conditions of the product. In order to carry out future-oriented product scenario expectations, five scenario element operation rules were summarized, a mapping relationship between demand evolution laws and operations was established, and a valuable scenario element variable inference strategy for future scenario conditions was formed. A heuristic case search method based on effect retrieval and scenario element matching was also introduced to get valuable innovative design solutions through systematic analogical design quickly. The feasibility of the proposed method was verified in the paper by a specific case study.

We acknowledge that our method was not robust in solving cases with insignificant responses to changes in the external environment and personnel conditions, and part of the process was also limited by the experience of the designer. Further work needs to improve the process by applying the method to different cases, while the softwareization process of the method needs to be advanced.

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REFERENCES

[1] Anggreeni, I.; Dervoort, M.C.: Tracing the scenarios in scenario-based product design a study to support scenario generation, Design Principles and Practices: An International Journal, 2(4), 2007, 123-136. https://doi.org/10.18848/1833-1874/cgp/v02i04/37564
[2] Anggreeni, I.; Dervoort, M.C.: Classifying scenarios in a product design process: a study towards semi-automated scenario generation, CIRP Design Conference, 2008, 1-6. https://doi.org/10.18848/1833-1874/cgp/v02i04/37564
[3] Baskerville, R.L.; Myers, M.D.: Design ethnography in information systems, Information Systems Journal, 25(1), 2015, 23-46. https://doi.org/10.1111/isj.12055

[4] Berkhout, F.; Hertin, J.; Jordan, A.: Socio-economic futures in climate change impact assessment: using scenarios as 'learning machines', Global Environmental Change, 12(2), 2002, 83-95. https://doi.org/10.1016/s0959-3780(02)00006-7
[5] Carroll, J. M.; Rosson, M.B.; Chin, G.; Koenemann, J.: Requirements development in scenario-based design, IEEE Transactions on Software Engineering, 24(12), 1998, 1156-1170. https://doi.org/10.1109/32.738344
[6] Chermack, T.J.; Lynham, S.A.; Van, D.M.L.: Exploring the relationship between scenario planning and perceptions of learning organization characteristics, Futures, 2006, 38(7): 767-777. https://doi.org/10.1016/j.futures.2005.12.010
[7] Durst, C.; Durst, M.; Kolonko, T.; Neef, A.; Greifc, F.: A holistic approach to strategic foresight: a foresight support system for the German federal armed forces, Technological Forecasting and Social Change, 97, 2015, 91-104. https://doi.org/10.1016/j.techfore.2014.01.005
[8] Feng, Y.; Zhao, Y.; Zheng, H.; Li, Z.W.; Tan, J.R.: Data-driven product design toward intelligent manufacturing: a review, International Journal of Advanced Robotic Systems, 17(2), 2020, 1-18. https://doi.org/10.1177/1729881420911257
[9] Fiorineschi, L.; Frillici, F.S.; Rotini, F.; Tomassini, M.: Exploiting TRIZ Tools for enhancing systematic conceptual design activities[J]. Journal of Engineering Design, 2018, 29(6): 259-290. https://doi.org/10.1080/09544828.2018.1473558
[10] Gero, J.S.: Recent design science research: constructive memory in design thinking, Architectural Science Review, 42(2), 1999, 97-99. https://doi.org/0.1080/00038628.1999.9696859
[11] Gick, M.L.: Holyoak, K.J.: Schema induction and analogical transfer, Cognitive Psychology, 15(1), 1983, 1-38. https://doi.org/10.1016/0010-0285(83)90002-6
[12] Hu, J.; Qi, J.; Peng, Y.: New CBR adaptation method combining with problem–solution relational analysis for mechanical design, Computers in Industry, 66, 2015, 41-51. https://doi.org/10.1016/j.compind.2014.08.004
[13] Hughes, J.A.; Bentley, R.; Randall, D.: Designing with ethnography: making work visible[J]. Interacting with computers, 5(2), 1993, 239-253. https://doi.org/10.1016/0953-5438(93)90020-T
[14] Hussain, M.; Tapinos, E.; Knight, L.: Scenario-driven road mapping for technology foresight, Technological Forecasting and Social Change, 124, 2017, 160-177. https://doi.org/10.1016/j.techfore.2017.05.005
[15] Jin, J.; Jia, D.; Chen, K.: Mining online reviews with a Kansei-integrated Kano model for innovative product design, International Journal of Production Research, 60(22), 2022: 6708-6727. https://doi.org/10.1080/00207543.2021.1949641
[16] Kishita, Y.; Hara, K.; Uwasu, M.; Umeda, Y.: Research needs and challenges faced in supporting scenario design in sustainability science: a literature review[J]. Sustainability Science, 2016, 11: 331-347. https://doi.org/10.1007/s11625-015-0340-6
[17] Kurakawa, K.: A scenario-driven conceptual design information model and its formation, Research in Engineering Design, 15(2), 2004, 122-137. https://doi.org/10.1007/s00163-004-0050-z
[18] Lee, H.; Geum, Y.: Development of the scenario-based technology roadmap considering layer heterogeneity: An approach using CIA and AHP, Technological Forecasting and Social Change, 117, 2017, 12-24. https://doi.org/10.1016/j.techfore.2017.01.016
[19] Lee, S. M.; Trimi, S.: Innovation for creating a smart future, Journal of Innovation & Knowledge, 3(1), 2018, 1-8. https://doi.org/10.1016/j.jik.2016.11.001
[20] Liu, L.M.; Tan, R.H.; Peng, Q.J.; Liu, W.; Zhang H.G.; Zhang, J.P.: et al. Function combination of product reconfiguration based on scenario analysis, Computer-Aided Design and Applications, 18(3), 2020, 532-544. https://doi.org/10.14733/cadconfp.2020.173-178
[21] Randt, N.P.: An approach to product development with scenario planning: the case of aircraft design. Futures, 71, 2015, 11-28. https://doi.org/10.1016/j.futures.2015.06.001

[22] Robin, C.; Regine, S.: Target Costing and Value Engineering, Productivity Press, New York, NY, 1997.
[23] Sakao, T.: A QFD-centred design methodology for environmentally conscious product design, International Journal of Production Research, 45(18-19), 2007, 4143-4162. https://doi.org/10.1080/00207540701450179
[24] Schuh, G.; Schultze, W.; Schiffer, M.; Rieger, A.; Rudolf, S.; Lehbrink, H.: Scenario-based determination of product feature uncertainties for robust product architectures, Production Engineering, 8(3), 2014, 383-395. https://doi.org/10.1007/s11740-014-0532-4
[25] Schweizer, V.; Kriegler, E.: Improving environmental change research with systematic techniques for qualitative scenarios, Environmental Research Letters, 7(4), 2012, 1-13. https://doi.org/10.1088/1748-9326/7/4/044011
[26] Shan, Z.J.; Ye, J.F.; Hao, D.C.; Xiao, P.G.; Chen, Z.D.; Lu, A.M.: Distribution patterns and industry planning of commonly used traditional Chinese medicinal plants in China, Plant Diversity, 44(3), 2022, 255-261. https://doi.org/10.1016/j.pld.2021.11.003
[27] Silva, R.H.; Kaminski, P.C.; Armellini, F.: Improving new product development innovation effectiveness by using problem solving tools during the conceptual development phase: Integrating Design Thinking and TRIZ, Creativity and Innovation Management, 29(4), 2020, 685-700. https://doi.org/10.1080/09544828.2018.1473558
[28] Shin J.E.; Sutcliffe, A.G.; Gregoriades, A.: Scenario advisor tool for requirements engineering, Requirements Engineering, 10, 2005, 132-145. https://doi.org/10.1007/s00766-004-0207-3
[29] Suri, J.F.; Marsh, M.: Scenario building as an ergonomics method in consumer product design, Applied Ergonomics, 31(2), 2000, 151-157. https://doi.org/10.1016/S0003-6870(99)00035-6
[30] Tan, R. H.: TRIZ and applications -the process and method of technological innovation, Higher Education Press, Beijing, 2010.
[31] Wang, H.; Fang, Z.; Wang, D.; Liu S.F.: An integrated fuzzy QFD and grey decision-making approach for supply chain collaborative quality design of large complex products, Computers & Industrial Engineering, 140, 2020, 106212. https://doi.org/10.1016/j.cie.2019.106212
[32] Xu, Q.; Jiao, R.J.; Yang, X.; Helander, M.; Khalid, H.M.; Opperud, A.: An analytical Kano model for customer need analysis, Design Studies, 30(1), 2009: 87-110. https://doi.org/10.1016/j.destud.2008.07.001
[33] Yang, C.Y.; Cai, W.: Extenics, Science Press, Beijing, BJ, 2014.
[34] Zhang, H.G.; Li Y.C.; Gao S.S.: Product technology foresight method guided by environmental profile transformation scenario analysis. Machine Design & Research, 37(02), 2021, 163-167+172. https://doi.org/10.13952/j.cnki.jofmdr.2021.0076
[35] Zhao, M.; Zhang, W.; Wang, G.: TRIZ enhancement and practical applications, China Machine Press, Beijing, BJ, 2015
[36] Zhong, R.Y.; Xu, X.; Klotz, E.; Newman, S.T.: Intelligent manufacturing in the context of industry 4.0: a review, Engineering, 3(5), 2017, 616-630. https://doi.org/10.1177/1729881420920029