www.cad-journal.net
Computer-Aided Design AND APPLICATIONS

Product Innovation Design Based on Scenario and LT Dimensions

Limeng Liu[1], Jinpu Zhang[2], Wenbing Chen[3], Chunlan Liang[4], Pengcheng Sheng[5] and Zhaoshuo Li[6]

[1] Hebei Vocational University of Technology and Engineering, Hebei Special Vehicle Modification Technology Innovation Center, liulimvp@163.com
[2] Hebei Vocational University of Technology and Engineering, jinpu_zhang@163.com
[3] Hebei Vocational University of Technology and Engineering, wenbing_chen32@163.com
[4] Hebei Vocational University of Technology and Engineering, 441705420@qq.com
[5] Hebei Vocational University of Technology and Engineering, 570463334@qq.com
[6] Hebei Vocational University of Technology and Engineering, 1902905977@qq.com

Corresponding author: Jinpu Zhang, jinpu_zhang@163.com

Abstract. Innovation design is designing products to meet future work needs. The future vision provided by scenarios can provide directions for product innovation design. This paper proposes a method for constructing new future scenario conditions, then identifies mismatched scenario units and critical points for product improvement by incorporating prototype products into scenario behaviors. The LT dimension is also introduced into the effect search process, and a heuristic case search method is proposed to obtain valuable innovative product design solutions suitable for the new scenario conditions through analogies by matching effect and scenario elements. The proposed design process model can support the conceptual design of product innovations capable of designing complex engineering systems across multiple disciplines, aiming to fill the existing research gaps in applying scenario and LT dimensions to the whole process of innovation design. Finally, the validity of the proposed methodology is verified by the innovative design of CMM dispensing equipment.

Keywords: scenario element; case retrieval; LT dimensions; innovative design
DOI: https://doi.org/10.14733/cadaps.2025.336-354

1 INTRODUCTION

The fundamental challenge in the process of innovative design is how to acquire creativity that is appropriate for the role of the future. Scenarios can transform broad insights from the future into concrete forms that designers can understand, effectively driving designers to evaluate and design based on dynamic actual scenarios [1].

The term “scenario” was first defined by Herman Kahn, who argued that based on the diversity and uncertainty of the future, the possible future and the descriptions of the ways to achieve them constitute a scenario and that the key to a scenario is to articulate the possible causal event chains and decision points [2]. In summary, scenarios have two main characteristics: they are uncertain and forward-looking and can describe a process that reflects the interaction between states of affairs. Based on these characteristics, scenarios are widely used for futuristic projections and representation of state-of-affairs processes. Based on the characteristics of the product design domain, this project adopts the definition of scenarios by Anggreeni [4]: scenarios mainly embody an explicit description of the hypothetical action process of a product at some stage of its life cycle.

Scenarios are a valuable tool for dealing with future uncertainty and complexity, and they have yielded essential results in business decision-making, policy development, military analysis, and forward-looking forecasting [3,20]. The application of scenarios in the field of design is also gaining importance. With the deepening of the concept of scenarios and the development of researchers' perceptions of product design, researchers have gained a deeper understanding of the relationship between the two. Gero [9] considered the product design process as a process of describing scenario analogy design that satisfies functional needs. Gick and Holyoak believed that creation arises from the transformation of conceptual spaces or the mapping of different knowledge systems, with the core being the transformation of knowledge from one scenario to another [10]. The meaning of the product depends more on the "scenario," emphasizing the importance of thinking better about the future from the present. Scenario analysis can help us identify the factors that will change the future so that we can make the right decisions and responses [12].

The significance and importance of scenarios in the design field are well recognized. As to how scenarios can guide the product innovation design process, some researchers have explored the role of the product in the expected uncertain future through scenario foresight to discover valuable future needs of the product. Suri and Marsh [18] proposed discovering product innovation opportunities by constructing scenario stories and sketches. Zhang et al [22] analyzed scenarios to predict the potential functionality and requirements of the product to effectively control the uncertainty of future customer needs and assist engineers in accurately finding the appropriate symbiotic technology from the massive cross-domain technical information. Liu et al [16] applied scenario analysis to product reconfiguration design and analyzed a product's internal systems and external scenarios to obtain potential functional units. Wang et al [21] used scenario information as supporting information in the requirements acquisition phase that improves the efficiency and accuracy of intelligent PSS configuration. Hussain et al [14] proposed a technology foresight methodology combining scenario planning and technology roadmap. Gui and Yong [11] used a sequence diagram model to describe sequences of interaction actions to satisfy specific goals and integrated scenarios into the functional design process of an intelligent system. Cornelissen et al [7] improved the timely availability of founding knowledge by constructing scenarios and tracking progress against scenario metrics to guide biotechnology R&D and innovation effectively. Geng et al [8] explored sustainable product and service design by constructing a scenario-driven two-tier demand network that seeks the functional needs of multifaceted stakeholders, integrating scenarios and QFD methods. Several studies have suggested techniques to incorporate scenarios in the innovation design process, but the theory requires further development. Identifying innovation opportunities based on scenarios and acquiring valuable innovative knowledge under imperfect situational conditions remains a significant challenge.

The scenarios can help predict the crucial aspects of a product for future use, providing a clearer understanding of the product's black box. However, cracking the scenario black box and obtaining the conceptual design solution of the product requires suitable methods. The design process that is based on analogical cases is an effective method to solve the scenario black box. Nevertheless, the traditional function-to-effect chain-based solution is ambiguous. The L-T dimensions kinematic system, consisting of feature length and time, can search for feasible effects through the multiplicative relationship between dimensions [5], which helps filter suitable analogous cases. This paper proposes to introduce the LT dimension into the analogical case solution process to guide the innovation process in an organized manner.

This paper builds on existing research in the field of scenario analysis and LT dimension to support methods and tools for the conceptual design of product innovations capable of designing complex engineering systems across multidisciplinary contexts, intending to fill the existing research gaps in the application of scenarios and LT dimension to the entire process of innovation design. First, construct new scenario conditions and incorporate them into the scenario behavior of the prototype product, and identify mismatched scenario units and critical points for product improvement. Then, the LT dimension is introduced into the effect search process, and a heuristic case-by-case search method is proposed by matching effect and scenario elements, which is used to obtain valuable innovative product design solutions adapted to new scenario conditions by analogy. The innovative design of the Chinese medicinal materials (CMMs) dispensing machine verifies the proposed method.

2 PROPOSED METHOD

2.1 Scenario-based Innovation Opportunities Discovery

The characteristics of a product are based on the scenarios in which it operates, and its functional requirements are closely related to these scenario conditions. In order to explore the key factors influencing the product's scenario conditions, several potential future scenarios can be projected. The product should be designed to navigate these scenarios and achieve the desired end state. By examining the product's behavior in the expected scenarios, it is possible to predict the possible characteristics of the product and identify opportunities for innovation.

2.1.1 Representation of scenario behavior process

The expression of product scenarios is the basis of future scenario reasoning. In this paper, we will draw on the method of literature [16]; the scenario is regarded as the evolution of the initial scenario node IS to the end scenario node ES, and the scenario node is simplified to the collection of scenario elements, where the scenario element E is expressed 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.

Scenario condition is the initial scenario state of the product scenario excluding the product, which is the initial condition of the product application. The set of scenario condition elements includes the elements that mark the completion of the primary design purpose, which are regarded as the core scenario elements(E_c), of which the core scenario elements of the initial state and the end state are denoted as E_{ci} and E_{ce}, respectively; the resources in the environment that may interact with the product application are regarded as the environment-related scenario elements(E_e); and the characteristics of the user group that play a specific role in the scenario evolution are regarded as the user-related scenario elements(E_u).

The evolution process of the scenario relies on the orderly operation of the scenario's external interaction behavior EB and internal inter-agency operation behavior IS, and the scenario behavior chain can be constructed[16], as shown in Figure 1.

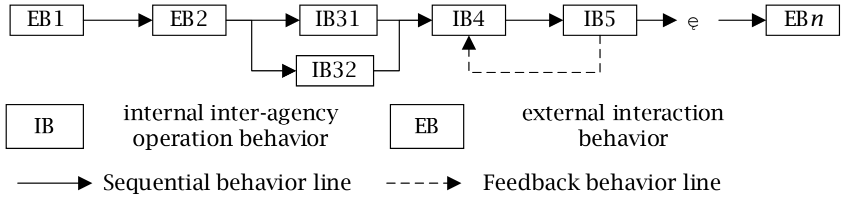

Figure 1: Scenario behavior chain of product action.

2.1.2 Construction of future scenario conditions

The construction of future product scenario conditions can draw on the intuitive logic school of mainstream scenario construction methods. This school of thought emphasizes identifying key variables early in the event, applying scenario logic to predict key factors, characterizing scenarios, and obtaining scenario information to aid decision-making [3]. This school of thought proposes three critical steps for constructing scenarios: setting up the scenario, identifying key drivers, and constructing scenarios based on critical uncertainties. Scenario planning in strategic management often uses PEST(Politics, Economy, Society, and Technology analysis) as a driver. However, the product scenario conditions are a discovery of future environmental elements, human factors, and core scenario elements, and it is an exploration process oriented to valuable needs. Considering the specificity of the product scenario, the following process of constructing the future scenario conditions of the product is proposed.

Step 1: Building a reference scenario

Based on the design task, a prototype product that meets the functional requirements to some extent is selected, one of its typical work scenarios is set, and the scenario elements are extracted.

Step 2: Identifying key scenario variables

Based on the types of scenario elements, a divergent thinking direction oriented towards the search of three types of scenario variables is proposed, as shown in Figure 2. Which points out the direction of scenario variable search for each type of scenario element. For example, core scenario elements can be searched for possible scenario variables through feature similarity, feature expansion, indicator reset, and feature deletion based on known element features; different thinking direction exploration from two aspects, namely, existing scenario search and new scenario setup, can be used to explore environment-related scenario variables; and user-related scenario variables can be obtained by exploring scenario variables through the four types of directions to guide the differential exploration of the user group.

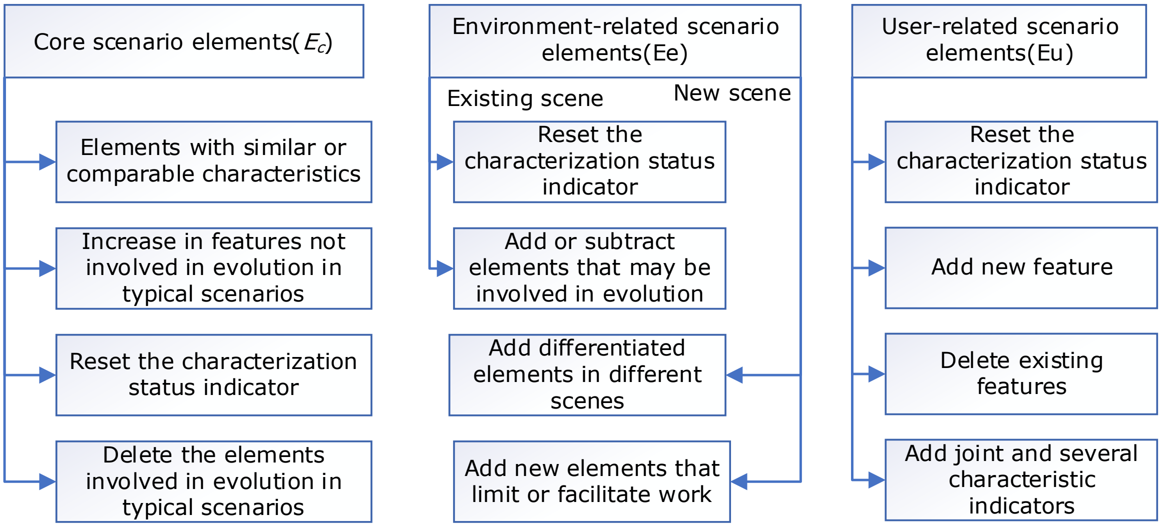

Figure 2: The divergent thinking process for scenario variables.

The above-suggested strategies for acquiring new scenario elements provide inspiring suggestions for R&D personnel to think out of the box, but this process needs to follow the following principles:

1) There is reasonableness for scenario variables appearing in the set scenario, which are universal and applicable;

2) On the premise of core scenario elements, new environment-related scenario elements and user-related scenario elements are constructed;

3) The acquisition of scenario variables is subject to the designer's experience and inspiration constraints. It can gradually spread from abstract to figurative and near-domain to cross-domain knowledge.

Step 3: Building new scenario conditions

Through the above exploration of the three types of elements in the future scenario conditions of the product, the critical scenario elements that may be faced when the product acts in the future are derived. A series of potential scenario conditions can be obtained by judging and selecting the three types of possible scenario elements for reorganization. In the judgment of reorganization conditions, compatibility means that the combination of crucial scenario elements will not interfere; reasonableness means that the critical scenario elements can be realized in the same scenario after the combination of each other and is in line with common sense; novelty means that the combined scenario elements are beyond the scenario boundaries of the product; and the judgment of the development potential is derived from the anticipation of the combination of the future value, which is jointly determined by the experience of the research and development personnel, the current situation of R&D in the enterprise, and the psychological expectations of the consumers. The experience of R&D personnel can determine it, as well as the current R&D situation of the enterprise and the psychological expectations of consumers. In reorganizing scenario conditions, various scenario elements may be Individual or multi-optional, and combining individual scenario element variables with the original scenario elements is also reasonable.

2.1.3 Identification of product innovation opportunities

As the key to driving the expected evolution of scenario conditions, the product ensures that the expected scenario occurs through interactions with scenario elements. By deducing the involvement of prototype products in the evolution of new scenario conditions, mismatched key scenario behaviors are identified, scenario black boxes are constructed, as shown in Figure 3, and necessary product characteristics are clarified as innovation opportunities.

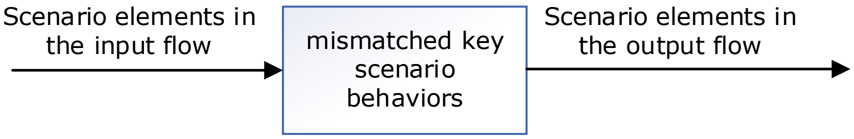

Figure 3: Scenario black box for mismatched units.

2.2 Scenario and LT-based Case Retrieval

A scenario's conditions and evolution law are crucial for a product to perform its intended functions. If new variables are introduced, the product's structure needs to be reorganized to meet the demands of the scenario black box. Case analog design helps get valuable design schemes efficiently and quickly. The key to this approach is to find a suitable analog case. A case search process based on LT dimensions is proposed as an effective way to find a suitable analog case.

2.2.1 LT dimensions and LT-matrix

The quantitative dimension reflects the basic properties of physical quantities. The production of various physical effects is closely related to various physical quantities, and the physical effects can be quantified and expressed through the functional relationship between physical quantities. It has been proposed that two fundamental quantities, length L (length) and time T (time), can describe other physical quantities, and the relationship between the two dimensions of L and T has been established [5,23] to represent them as LT matrix, as shown in Table 1.

The two-dimensional LT scale follows the law of physical conservation and establishes the relationship between the LT scale and the physical constants, and the operation of the scale follows the law of exponential operation; for the LT scale, if the scales of physical quantity A and physical quantity B are denoted as $L^{\alpha}T^{\beta}$ and $L^{\gamma}T^{\delta}$ respectively, the multiplication of the two physical quantities is

$$A \cdot B = L^{\alpha}T^{\beta} \cdot L^{\gamma}T^{\delta} = L^{\alpha+\gamma}T^{\beta+\delta} \quad (2.1$$

Dimensions	L^{-1}	L^{0}	L^{1}	L^{2}	L^{3}	L^{4}
T^{-4}		$L^{0}T^{-4}$	The gradient of gravity or pressure	Stress Strain	Surface tension Rigidity	Force
T^{-3}		$L^{0}T^{-3}$	Current density	Electro-magnetic field intensity Toughness Flexibility	Current Mass loss	Movement amount Pulse
T^{-2}	$L^{-1}T^{-2}$	Mass density Angular acceleration	Magnetic flux density Acceleration	Potential difference	Mass Electric flux	Electric flux
T^{-1}	Volume charge density	Frequency	Velocity	Two-dimensional margin Speed of area change	Loss of volume	$L^{4}T^{-1}$
T^{0}	Change conductivity	Dimensionless constant	Length Capacity Self-induction	Surface area	Volume	The Distribution of the volume along the length
T^{1}	Electric conductivity	Cycle	$L^{1}T^{0}$	$L^{2}T^{1}$	$L^{3}T^{1}$	
T^{2}	$L^{-1}T^{2}$	$L^{0}T^{2}$	$L^{1}T^{2}$	$L^{2}T^{2}$		
T^{3}	$L^{-1}T^{3}$	$L^{0}T^{3}$	$L^{1}T^{3}$			

Table 1: LT-matrix established by two-dimensional physical dimension

According to the operation law of LT measure, the inference operation between corresponding physical quantities can be carried out, for example, there are a total of m physical quantities of C_1, C_2, ... C_m, corresponding to the measure [C_1], [C_2] ... [C_m], and its combination of the measure is [C], and there are

$$[C] = [C_1]^{\alpha} \cdot [C_2]^{\beta} \cdots [C_m]^{\gamma} \quad (2.2)$$

In the formula, α, β, γ denote the number of powers of the corresponding measure, respectively. The operation of the LT scale is critical to its auxiliary representation of relationships between physical quantities and intellectual reasoning.

Rodenacker and Koller [15] compiled a compendium of physical effects to summarize the LT scale effects knowledge base, specifying the input and output scales of the effects to aid the effects knowledge search process.

2.2.2 Effect reasoning based on LT dimensions

The search of effect and effect chain is the key to finding innovative knowledge, using the LT dimension as a search tool, following specific rules, and combining the requirements of the required search function back to the product scenario behavior. According to the resource situation in the product scenario, matching the critical element characteristics of the back-and-forth sequence of the scenario behavior, the following effect search steps are proposed, as shown in Figure 4.

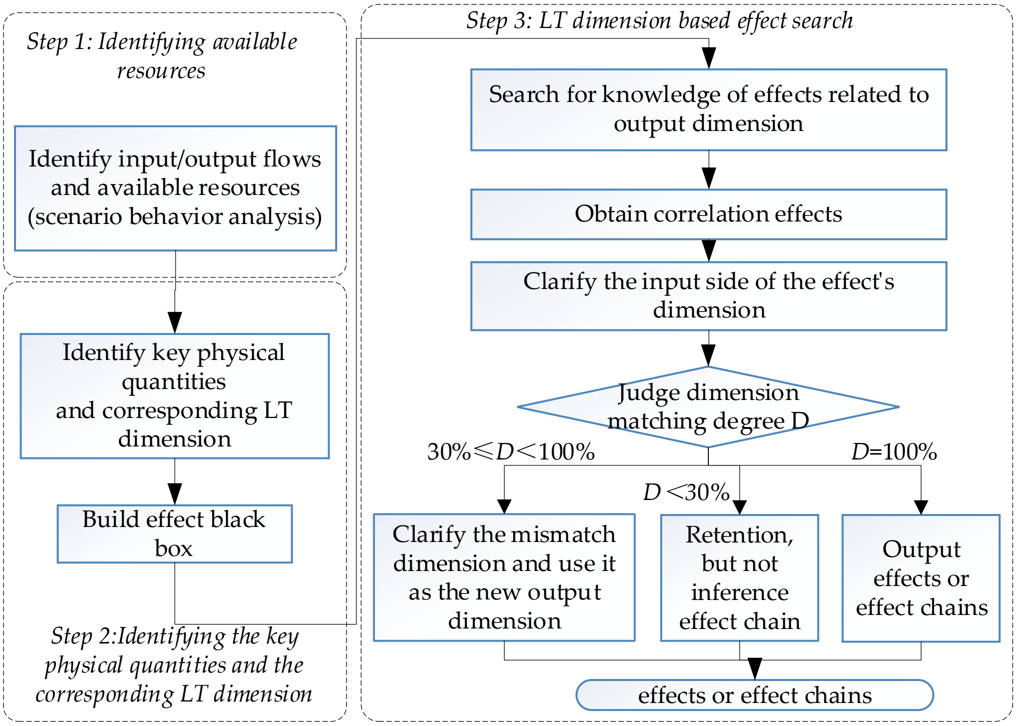

Figure 4: Effect search process model based on LT dimension.

Step 1: Identifying available resources

The black box of scenarios corresponding to innovation opportunities is analyzed to clarify the input and output flows. In order to make the search effects more targeted, trace the features back to the expected scenario behavior unit, clarify its pre-order scenario elements and post-order scenario elements as the expected input and output flows, and obtain available resources from the expected scenario.

Step 2: Identifying the vital physical quantities and the corresponding LT dimensions

The scenario elements corresponding to the input/output flows are analyzed to identify the core scenario elements among them and to specify their dominant and principle characteristics as alternative physical quantities for effect inference. Causal analysis [19] is used to find the vital physical quantities at the function's output when the function performs its expected work.

The output flows are converted to LT dimensions as essential physical quantities, and the input flows or the resources available to the system and supersystem are converted to LT dimensions, then the effect black box, as shown in Figure 5.

Figure 5: Effect black box.

Step 3: LT dimension-based affect search

The expected input and output dimensions are set to be C_{IP} and C_{OP}, respectively. Since the output side of the effect black box is the physical quantity most needed to complete the scenario behavior, the appropriate effect/effect chain is gradually searched for, starting from the output side.

1) Find the set of effects from the knowledge base of LT dimension effects whose LT dimension at the output side coincides with the C_{OP}. For the obtained knowledge of the effect, if there are n input dimensions on the right-hand side of the inclusion equation of the effect and m of the dimensions in the available resources in the system coincide with it (m ≤ n), the match of the dimensions is

$$D=\frac{m}{n}\times 100\% \quad (2.3)$$

If D=100%, it is consistent with the principle of dimension compatibility and can be directly used as potential effect knowledge; if D < 100%, the existing resource condition is missing the element that provides a particular essential dimension.

The principle of dimension compatibility: The dimensions are set to be C_1 and C_2, respectively. C1 and C2 have the same name, and their degree of agreement is D_c=100%.

For the effect knowledge with D < 100%, the effect inference is continued with the missing dimension of resource matching as the output. After judging the obtained effect knowledge, stop if it is compatible; otherwise, continue reasoning, and finally, the effect chain that meets the requirements can be derived, as shown in Figure 6. C_{i1}, C_{i2}, C_{i3}, C_{i4}, and C_{ik} are all the available resources in the existing dimension, and Cin is the mismatched dimension for the secondary effect inference.

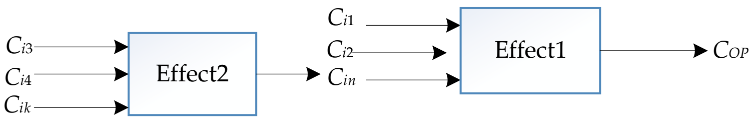

Figure 6: Effect chain based on LT dimensions reasoning.

Through discussion and analysis with innovation experts, taking into account the value and complexity of the search effect, it is suggested that when performing effect chain inference, the matching degree D should be more excellent than 30%, and the number of inferences should not exceed five times.

2.2.3 Scenario-oriented case retrieval process

The above processes are applied to search for the appropriate effect or chain 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 effect's input 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 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.

It is essential to choose appropriate search terms to effectively search for relevant cases after selecting the desired effect. However, it is uncommon for the effect's name to be mentioned in patent texts or product descriptions. Keywords related to the effect can be converted into a series of functionally relevant verbs based on the behavior of the case application.

For example, the Venturi effect can associate the vacuum cleaner with the desired "move" function and extract keywords such as "air suction," "suction," and "absorption." These keywords create search formulas such as "function keywords and/or effect keywords" for patents or related product searches.

After retrieving the cases, the structure of the new scenario behavior required for its implementation can be extracted. Then, a suitable case as an analogous source can be selected by considering factors such as complexity, matching, improvement difficulty, cost, and more.

3 SCENARIO AND LT DIMENSIONS -BASED INNOVATION DESIGN PROCESS

Scenarios have unique advantages in the innovation opportunity discovery phase [6], and the LT dimensions-based case search process can help designers quickly obtain feasible reference scenarios and design solutions through analogies [13]. Therefore, this study proposes an innovative design process based on scenarios and LT dimensions, which includes five steps, as shown in Figure 7.

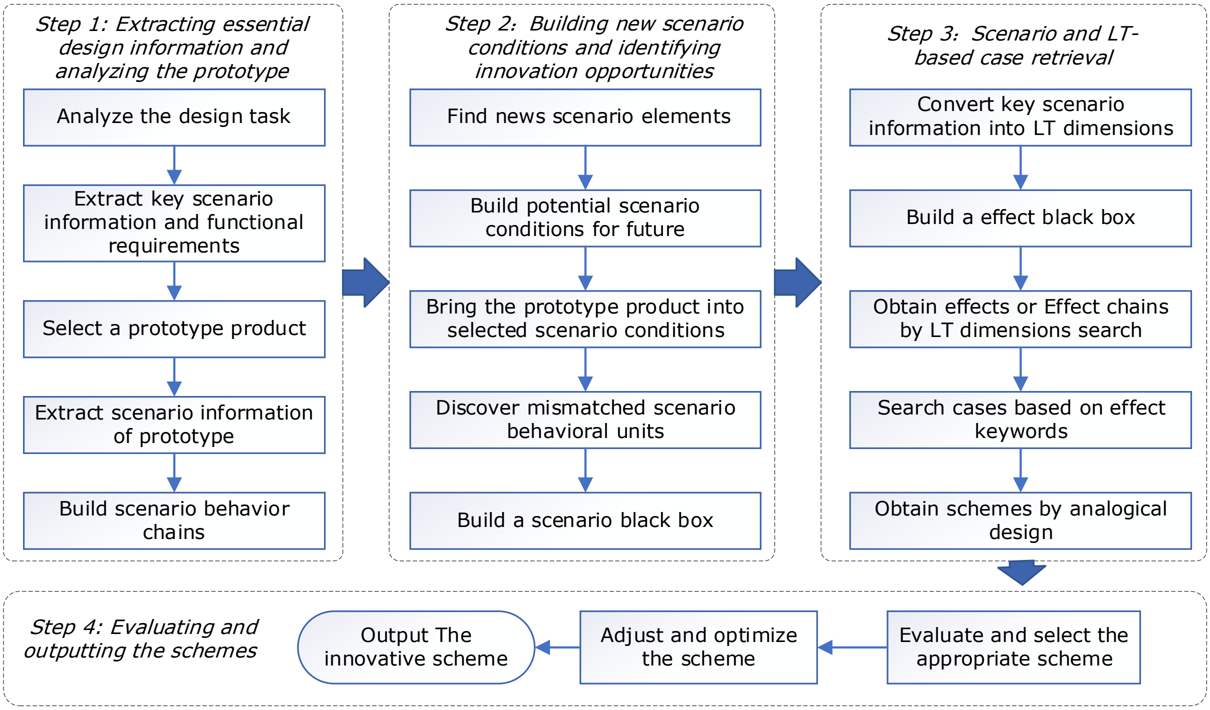

Figure 7: An innovative design process based on scenarios and LT dimensions.

Step 1: Extracting essential design information and analyzing the prototype

Firstly, the design task needs to be analyzed in detail. Then, known scenario elements in the future product scenario are identified, usually including essential initial and ending scenario elements. The dominant functional requirements and critical functional attributes can also be elucidated.

Through market research or patent search, select a product that satisfies the design requirements to a certain extent as a prototype; then, based on the extraction and expression of product scenario elements in the literature [16], the typical scenario information of the prototype product is extracted. The scenario behavior chain is constructed based on the expected evolution process of the scenario.

Step 2：Building new scenario conditions and identifying innovation opportunities

Based on the process described in Section 2.1, the critical scenario elements in the prototype product are used as a basis for obtaining key scenario elements that may exist in future product scenarios through directed thought dispersion on the scenario elements. Then, the potential conditions of the future scenario are obtained by reorganizing the scenario variables based on the scenario logic. By bringing the prototype product into the selected new scenario conditions, unsupported scenario behavior units are identified based on the interaction logic relationship, and the scenario black box is constructed as a critical opportunity for innovation design.

Step 3：Scenario and LT-based case retrieval

According to the process described in Section 2.2, search for suitable analogical cases based on the scenario black box and LT matrix, and through the analogical design process, replace or add the relevant structures to the relevant behaviors and adjust them according to the actual situation to obtain an innovative design solution.

Step 4: Evaluating and outputting the scheme

The evaluation contributes to the selection of the optimal scheme, which can be evaluated based on the design key indicators and their weight scores with the following formula:

$$V_i = \sum_{j=1}^{n} W_j \times k_{ij} \tag{3.1}$$

where V_i is the coefficient value of scheme i, W_j represents the weight of the jth evaluation index; k_{ij} represents the relative value coefficient of the ith scheme relative to the benchmark scheme in the jth evaluation index. The prototype scheme is regarded as the benchmark scheme with score V_0.

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, cost, and more.

The results of the ratings determine the priority of the solution designs, with higher-priority designs being further optimized and refined to output viable and innovative solutions. Finally, a valuable innovative design scheme can be output by adjusting and optimizing the selected scheme.

4 CASE STUDY

Chinese medicine is vital in treating diseases and saving people's lives. The precise configuration of Chinese medicinal materials (CMMs) is the basis for ensuring the efficacy of treatment [17]. The traditional way for medical personnel to weigh manually is more underground in terms of efficiency, and there is an urgent need to design a device for the automatic configuration of CMMs.

4.1 Extracting Initial Design Information

Based on the design problem and background, analyze the design task and make clear that the leading demand for innovative design is "dispensing CMMs，" and the main body of the scenario element is "CMMs." The critical scenario information extracted from the design task is

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

4.2 Analyzing the Typical Product Scenario of Prototype Product

After analyzing relevant patents and devices, we selected a CMMs configuration device shown in Figure 8 as a prototype. which relies on the flipping roller and gravity to make the CMMs fall through the weighing platform to calculate the amount of CMMs and feedback control sealing plate to determine the opening and closing of the CMMs outlet.

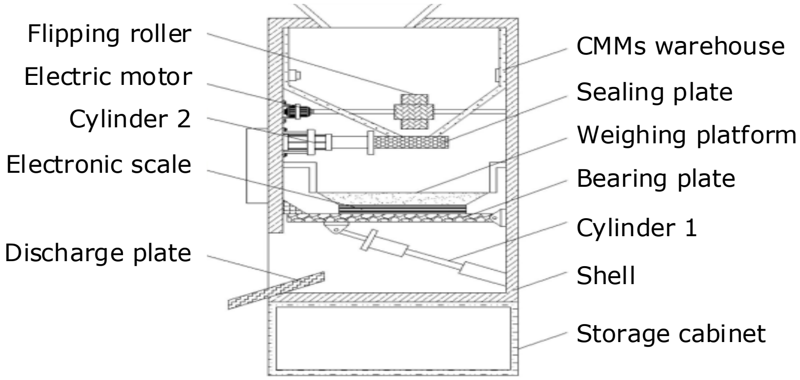

Figure 8: A gravity type CMMs dispensing equipment.

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_0Eci= [*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 core scenario element of the ending state is P_0Ece= [*CMMs*, state, *quantitatively stored in one bag*]. The scenario behavior chain of the prototype product is shown in Figure 9.

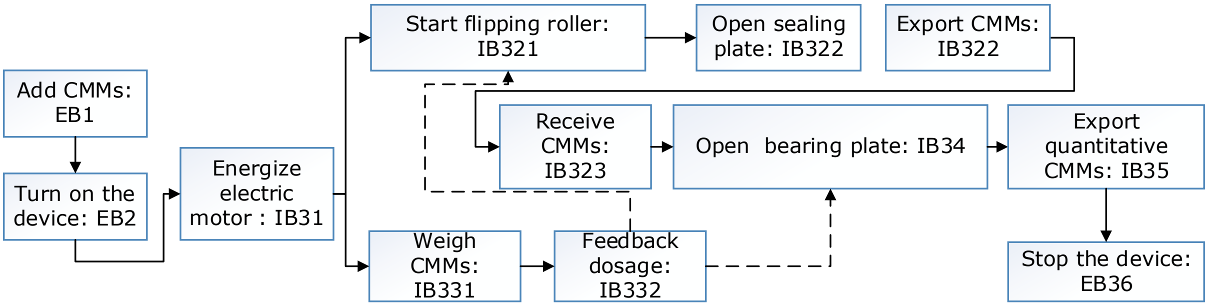

Figure 9: The scenario behavior chain of the prototype product.

4.3 Building New Scenario Conditions and Identifying Innovation Opportunities

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:

For the core scenario elements, through resetting the metrics of the shape of the CMMs, P_1Eci= [*CMMs*, *physical shape, irregular*] and P_2Eci= [*CMMs*, *physical shape*, *granules and powder*] can be obtained. P_3Eci= [*western medicine*, *type*, *drug*] can be obtained by finding similar feature themes. By resetting the state characteristics of the core scenario elements, P_4Ece=[*CMMs*, *state*, *quantitative continuous multiple bags*] can be obtained

For environment-related scenario elements, P_1Ee= [*socket*, *status*, *no electricity*] can be obtained by deleting the key elements in the existing environment; P_2Ee= [*small pharmacy*, *characteristics*, *narrow space*] and P_3Ee= [*special area*, *status*, *hot and humid*] can be obtained through the discovery of the new scenarios;

For the user-related scenario elements, P_1Eu=[*user*, *level of participation*, very *little or no*] can be obtained by resetting the user engagement; P_2Eu=[*user*, *component*, *patient or family*] can be obtained by resetting the user component, and further, the linked characteristic element can be obtained as P_3Eu=[*patient or family members*, *characteristics*, *no knowledge about CMMs*].

The following feasible future scenario conditions or configuration conditions were derived by recombining and adjudicating, in addition to the new scenario conditions, with only one scenario variable added:

P_1Eci + P_2Eci + P_3Eci + P_1Ee + P_1Eu + Original conditions form the scenario conditions that target multiple forms of CMMs or western medicine tablets with no or few users and no external power supply;

P_1Ee + P_3Ee +P_2Eu + P_3Eu + Original conditions form scenario conditions for workplaces such as hot and humid area, where there is no external power supply and user applicability;

P_2Eci + P_4Ece is used to form configuration conditions that support powdered or granular CMMs and allow for continuous dosing of CMMs.

The powder or granular CMMs can be quantitatively configured several times with electric power in hospitals selected for further design. However, the prototype product could not fulfill the scenario variables P_2Eci= [*CMMs*, *physical shape*, *granules and powder*] due to its inability to perform the configuration of powdered CMMs, and P_4Ece = [*CMMs*, *status*, *quantitative continuous multiple bags*] cannot be met by prototype product.

P_2Eci was brought into the scenario behavior process of the prototype product; the strong relevant scenario behavior unit of P_2Eci is "IB322: Export CMMs." The black box of the mismatched key scenario behaviors is shown in Figure 10. The scenario also includes air, pressure, gravity, electricity, rotary power, and other resources.

Figure 10: Scenario black box for mismatched unit.

4.4 Scenario and LT-based Case Retrieval

After analysis, the critical flow in the IB322 is CMMs, and it is found that the physical quantity corresponding to the dominant characteristics is distance d with LT dimension L^1T^0. The physical quantity corresponding to the principle characteristics is velocity v with LT dimension L^1T^{-1}. By causal analysis, the output of the future effect is force F, with LT dimension L^4T^{-4}, as shown in Figure 11.

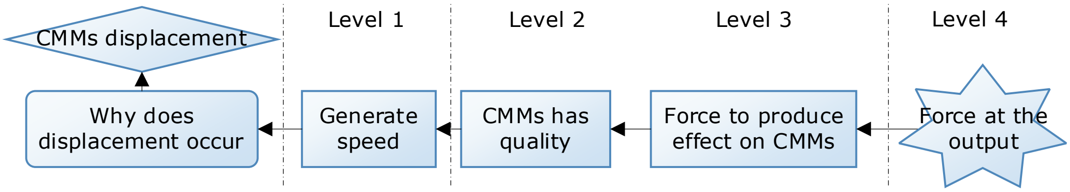

Figure 11: Causal analysis.

The physical quantities corresponding to input flow CMMs are distance d, mass m, volume V, etc., and the corresponding LT dimensions are L^1T^0, L^3T^{-2}, L^0T^{-1}, L^3T^0. The physical quantities corresponding to kinetic energy are mass, angular velocity, velocity, etc., and the LT dimensions are L^3T^{-2} and L^1T^{-1}. The physical quantities corresponding to electrical energy are current I, voltage U, etc., and the LT dimension is L^3T^{-3}、L^2T^{-2}. Time, gravitational resources, and air corresponding to the physical quantities of time t, gravitational acceleration g, and air density ρ, have LT dimensions of L^0T^1, L^1T^{-2}, and L^0T^{-2}, respectively. An effect black box can be constructed, as shown in Figure 12.

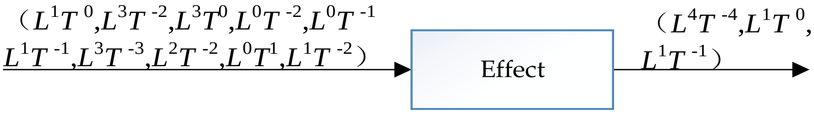

Figure 12: Effect black box.

The effect search is performed according to the input and output dimensions, and the set of matching effects is obtained by finding the corresponding LT dimension effect base[15]. as shown in Table 2.

Effect Name	Formula	Input physical quantity	Output physical quantity	Input LT dimension	Output LT dimension
Elastic deformation effect	F=k·x	k, x	F	L^4T^{-3}, L^1T^0	L^4T^{-4}
Barometric effect	$F=P\cdot S$	P, S	F	L^2T^{-4}, L^2T^0	L^4T^{-4}
Centrifugal force effect	$F=m\cdot w^2\cdot r$	m, w, r	F	L^3T^{-2}, L^0T^{-1}, L^1T^0	L^4T^{-4}
Magnetic attraction effect	$F=H\cdot Q$	H, Q	F	L^3T^{-2}, L^2T^{-1}	L^4T^{-4}
Archimedes' spiral effect	$r=a+b\cdot\theta$	b	r	L^1T^0	L^1T^0
Movement Principle	$L=v\cdot t$	v , t	L	L^1T^{-1}, L^0T^1	L^1T^0
Vibration Principle	$x=A\cos(\omega t+\varphi)$	ω, t	x	L^0T^{-1}, L^0T^1	L^1T^0

Table 2: A set of effects consistent with L^4T^{-4}, L^1T^0 and L^1T^{-1}.

It is found that most of the above effects have a D=100%, and the magnetic suction effect has a D=0%, which can be used as a separate heuristic term, but 0%<30% does not carry out the inference of the effect chain. The barometric effect has D=50%. Since 30%<50%<1, the effect chain can be inferred. The mismatched physical quantity is pressure P with LT dimension L^2T^{-4}; a set of effects can be obtained by finding the corresponding LT dimension effect base [15], as shown in Table 3.

Effect Name	Formula	Input physical quantity	Output physical quantity	Input LT dimension	Output LT dimension
Pascal effect	$P=\rho \cdot g \cdot h$	ρ, g, h	P	L^0T^{-2}, L^1T^{-2}, L^1T^0	L^2T^{-4}
Coanda effect	$P=C-\frac{1}{2}\rho \cdot v^2-\rho \cdot g \cdot h$	ρ, v, g, h	P	L^0T^{-2}, L^1T^{-1}, L^1T^{-2}, L^1T^0	L^2T^{-4}
Venturi effect	$P_a-P_b=\frac{1}{2}\rho \cdot (v_b^2-v_a^2)$	ρ, v	ΔP	L^0T^{-2}, L^1T^{-1},	L^2T^{-4}

Table 3: A set of effects consistent with L^2T^{-4}.

The above effects are found to have D=100%, so they can all form a new effect chain with the barometric effect, and the number of inferences is 1, which meets the inference rule. The chain of effects composed of the barometric effect, Pascal effect, Coanda effect, and Venturi effect are shown in Figure 13(a), Figure 13(b), and Figure 13(c), respectively.

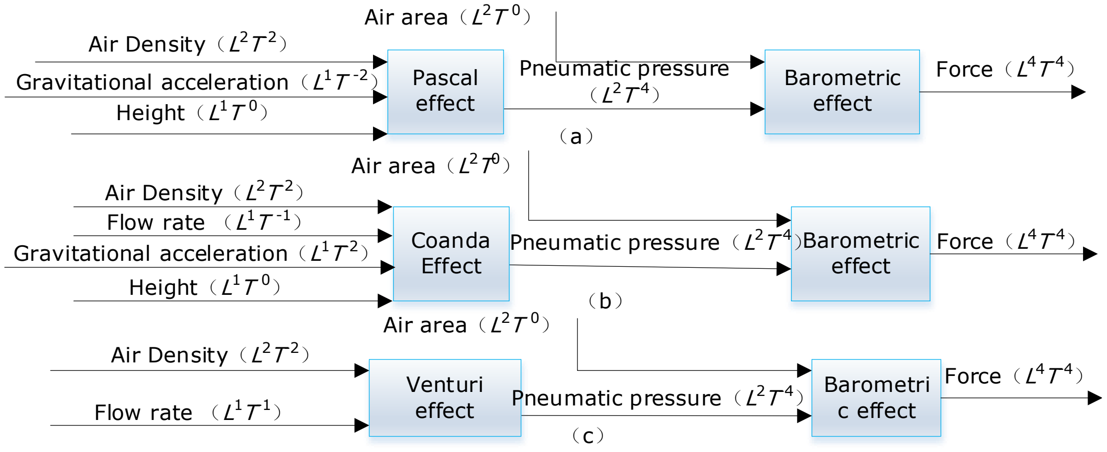

Figure 13: (a) Effect chain composed of Pascal effect and Barometric effect; (b) Effect chain composed of Coanda effect and Barometric effect; (c) Effect chain composed of Venturi effect and Barometric effect.

"Air suction" can be extracted as the keyword from the Venturi and Barometric effects; the main function can be abstracted as "move object." Then, using ("air suction" and "move object") as the retrieval formulas for patent retrieval, Over 100 related patents were searched, and a suitable case called "A negative pressure automatic feeding device" was selected, as shown in Figure 14(a), then an innovation scheme one is got through analogy improvement as shown in Figure 14(b).

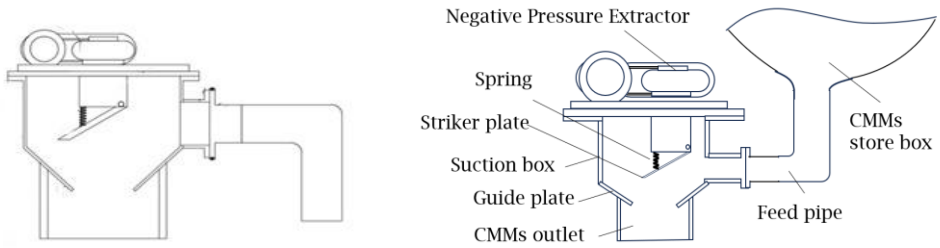

Figure 14: (a) A negative pressure automatic feeding device, (b) Schematic diagram of negative pressure type CMMs transport mechanism.

Similarly, the choice of the Archimedean spiral effect leads to the reference case Figure 15(a), which by analogy leads to scheme 2, as shown in Figure 15(b).

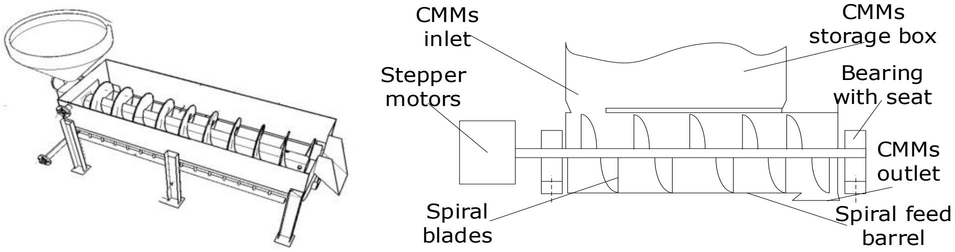

Figure 15: (a) A plastic powder feeding device, (b) Schematic diagram of the screw feeding type CMMs transport mechanism.

4.5 Evaluating and Outputting the Scheme

After expert analysis, the following key evaluation indicators M={speed, accuracy, reliability, novelty, applicability, cost }, weight assignment w=(0.16, 0.18, 0.15, 0.12, 0.16, 0.23)^T are determined. A relative assignment is obtained by comparison with benchmark technology, as shown in Table 4.

Indicators / Schemes	Speed	Accuracy	Reliability	Novelty	Applicability	Cost
Benchmark	1	1	1	1	1	1
Scheme 1	2.1	0.8	0.9	1.5	1.2	0.7
Scheme 2	1.8	1.3	1.2	1.2	1.8	1.1

Table 4: Evaluation and assignment of schemes.

Taking the assignment value into formula (3.1). After calculation, V_1=1.148V_0, V_2=1.387V_0. Due to V_2>V_1>V$_0$, scheme 2 can be used as the preferred design, and scheme 1 as an alternative. In the same way, an innovative scheme design of a continuous weighing and collecting device is obtained, as shown in Figure 16.

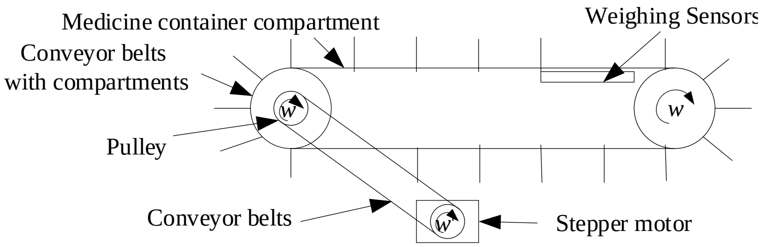

Figure 16: Schematic diagram of continuously dispensing multiple CMMs mechanism.

A new CMMs dispensing machine can be obtained by integrating and optimizing the schemes, as shown in Figure 17. The experiment shows that the new scheme can realize design requirements, and the output speed and accuracy are better than the prototype product.

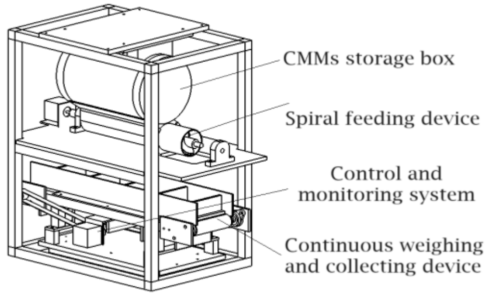

Figure 17: An innovative CMMs dispensing equipment.

5 METHOD EVALUATION AND DISCUSSION

In order to evaluate the proposed method, our method was compared with three existing methods in terms of applicability, complexity, learning difficulty, and efficiency of high-quality scheme outputs, which were rated by ten experts in the field of innovation on a scale 1 (worst) to 5 (best), and after averaging, the results were obtained, as shown in Figure 18.

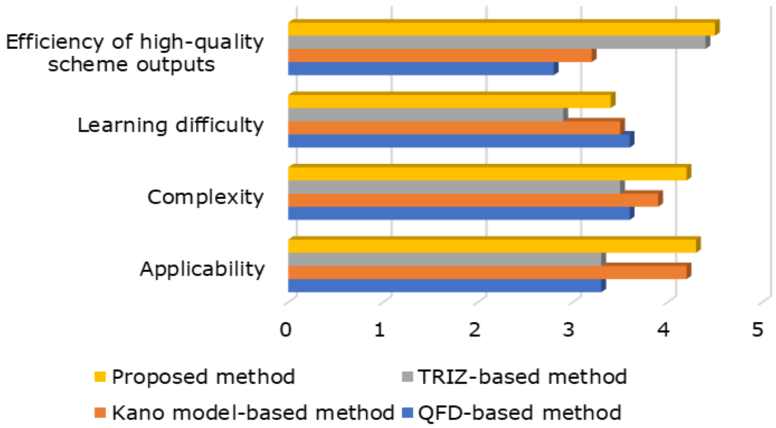

Figure 18: Results of the four-method controlled test.

Based on the Figure 8, the proposed method has certain advantages in applicability, innovation efficiency, and other aspects compared to traditional innovative design methods. The foresight of the scenario ensures the rationality and diversity of innovative design solutions, the interactivity of the scenario ensures the practicality of the design, and the introduction of LT ensures the solution's novelty and logicality. This method has specific guiding significance and value.

6 CONCLUSIONS

This paper presents a new design process for innovative product design based on scenario and LT dimensions. The proposed method attempts to introduce scenario vision into the product design process. Several possible scenario conditions are constructed by anticipating vital elements of the future. By integrating prototype products into new scenario behaviors, mismatched scenario units and critical points for product improvement are identified. It also provides essential scenario features for acquiring analogical cases. Meanwhile, a new way to apply LT dimensions for knowledge acquisition is explored. A heuristic case search method based on the LT dimension effect retrieval method and scenario element matching is used to guide designers in obtaining valuable innovative product design solutions through analogy.

The proposed method combines the advantages of scenarios and LT dimensions in design. It integrates the two into product design to form a systematic design process model, which considers the factors of multi-stakeholders, environmental variables, and analogical knowledge matching and helps the designer quickly obtain the conceptual design solution for product innovation. A specific case study verified the feasibility of the proposed method.

Despite the advantages of the new design method, there are some limitations in this study: The method proposed in this paper relies on the experience and inspiration of the designer in the process of new scenario element acquisition and LT-based effect inference, making the acquisition less efficient and more affected by cognitive variability; during the case study, a new structural solution for the CMMs dispensing was built based on the proposed process model. Although the overall performance of this new concept structure has been improved compared to the prototype, there are opportunities for further improvements. In the future, computer-aided design will be further established to improve innovation efficiency.

ACKNOWLEDGEMENTS

This research is sponsored by Science and Technology Research Project of Colleges and Universities of Hebei Province (QN2024001, QN2024284), the Innovation Capacity Enhancement Project of XingTai (2023ZZ099, 2023ZZ094)

Limeng. Liu, https://orcid.org/0000-0002-9365-1800
Jinpu Zhang, https://orcid.org/0000-0002-6813-8466
Wenbing Chen, https://orcid.org/0009-0005-5316-3350
Chunlan Liang, https://orcid.org/0009-0002-6150-9225
Pengcheng Sheng, https://orcid.org/0009-0004-0529-9635
Zhaoshuo Li, https://orcid.org/0009-0000-1629-3504

REFERENCES

[1] Wiebe, K.; Zurek, M.; Lord, S.; Brzezina, N.; Gabrielyan, G.; Libertini, J.: Scenario development and foresight analysis: exploring options to inform choices, Annual Review of Environment and Resources, 43, 2018, 545-570. https://doi.org/10.1146/annurev-environ-102017-030109

[2] Kahn, H.; Wiener, A. J.: The next thirty-three years: a framework for speculation, Daedalus, 1967, 705-732. https://doi.org/10.2307/20027066

[3] Amer, M.; Tugrul, U.D.; Antonie, J.: A review of scenario planning, Futures, 46, 2013, 23-40. https://doi.org/10.1016/j.futures.2012.10.003
[4] 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
[5] Bartini, R.O.: Relations between physical constants, Progress in Physics, 3, 2005, 34-40. https://doi.org/10.1126/science.75.1939.243.b
[6] Carroll, J. M.; Rosson, M.B.; Chin, G.; Koenemann, J.: Requirements development in scenario-based design, IEEE Transactions on Software Engineering, 24, 1998, 1156-1170. https://doi.org/10.1109/32.738344
[7] Cornelissen, M.; Małyska, A.; Nanda, A.K.; Lankhorst, R.K.; Parry, M.: Biotechnology for tomorrow's world: scenarios to guide directions for future innovation, Trends in biotechnology, 39(5), 2021, 438-444. https://doi.org/10.1016/j.tibtech.2020.09.00
[8] Geng, X.; Li, Y.; Wang, D.; Zhou, Q.: A scenario-driven sustainable product and service system design for elderly nursing based on QFD, Advanced Engineering Informatics, 60, 2024, 102368. https://doi.org/10.1016/j.aei.2024.102368
[9] Gero, J.S.: Recent design science research: constructive memory in design thinking. Architectural Science Review, 42, 1999, 97-99. https://doi.org/10.1080/00038628.1999.9696859
[10] Gick, M.L.; Holyoak, K.J.: Schema induction and analogical transfer, Cognitive Psychology, 15, 1983, 1-38. https://doi.org/10.1016/0010-0285(83)90002-6
[11] Gui, F.; Chen, Y.: A scenario-integrated approach for functional design of smart systems, AI EDAM, 35(2), 2021, 165-179. https://doi.org/10.1017/s0890060420000487
[12] Hu, J.; Zhou, K.: From user scenario to design strategy: practice research on product innovation, In Advances in Human Factors and System Interactions, 2017: 377-382. https://doi.org/10.1007/978-3-319-41956-5_33
[13] 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
[14] Hussain, M.; Tapinos, E.; Knight, L.: Scenario-driven road-mapping for technology foresight, Technological Forecasting and Social Change, 2017, 124: 160-177. https://doi.org/10.1016/j.techfore.2017.05.005
[15] Koller, R.; Kastrup, N.: Principle solutions for design of technical products (2nd ed.). Springer-Verlag, Berlin, 1998.
[16] Liu L. M.; Sheng, P.C.; Ma, J.G.; Wang, F.; Tan, R.H.: Product Innovation Design Method Based on Scenario, Computer-Aided Design and Applications, 21(3), 2023, 444-462. https://doi.org/10.14733/cadaps.2024.444-462
[17] Miao, P.; Li, Y.; Fan, Q.; Ni, L.; Liu, S.Q.; Li, J.; Zhang, S.: Research on Chinese medicinal materials cultivation: A bibliometric and visual analysis, Heliyon, 10(7), 2024, e28637. https://doi.org/10.1016/j.heliyon.2024.e28637
[18] Suri, J.F.; Marsh, M.: Scenario building as an ergonomics method in consumer product design, Applied ergonomics, 31, 2000, 151-157. https://doi.org/10.1016/s0003-6870(99)00035-6
[19] Tan, R. H.: TRIZ and applications -the process and method of technological innovation, Higher Education Press, Beijing, 2010.
[20] Van den berg, P.; Scholten, D.; Schachter, J.; Blok, K. Updating scenarios: A multi-layer framework for structurally incorpo-rating new information and uncertainties into scenarios, Futures, 130, 2021, 102751. https://doi.org/10.1016/j.futures.2021.102751
[21] Wang, Z.; Chen, C.H.; Zheng. P.; Li, S.; Song, W.: A hypergraph-based approach for context-aware smart product-service system configuration, Computers and Industrial Engineering, 2022, 163: 107816. https://doi.org/10.1016/j.cie.2021.107816

[22] Zhang, L.; Tan, R.H.; Peng, Q.J.; Mao; R.Z.; Liu, L.M.: Product innovation based on the host gene and target gene recombination under the technological parasitism framework, Advanced Engineering Informatics, 59, 2024, 102341. https://doi.org/10.1016/j.aei.2023.102341
[23] Zhang, P.; Nie, Z.F.; Dong, Y.F; Zhang, Z.; Yu, F.; Tan, R.H.: Smart concept design based on recessive inheritance in complex electromechanical system, Advanced Engineering Informatics, 43, 2020, 101010. https://doi.org/10.1016/j.aei.2019.101010