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A Decision-Making Framework for Early-Stage Industrial Intelligent Engineering Innovation Based on Extenics and TRIZ

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Abstract: The early stages of engineering innovation are typically characterized by high levels of uncertainty, strong dependence on expert experience, and complex coupling among design objectives, manufacturing constraints, and solution maturity. These characteristics make the associated decision-making processes difficult to formalize and reproduce. To address this challenge, an industrial intelligence framework integrating Extenics and the Theory of Inventive Problem Solving (TRIZ) was proposed to support structured reasoning and consistent decision-making in the early phase of engineering innovation. Within the proposed framework, engineering objectives, constraint conditions, and solution maturity are represented as structured industrial knowledge elements, enabling unified processes of conflict identification, rule-based reasoning, and multi-criteria evaluation. Extenics is employed to construct formal representations of problem elements and their interrelationships, while TRIZ is utilized to support systematic principle-based resolution of contradictions. Through this integration, engineering decision-making is shifted from reliance on implicit experiential knowledge toward an explicit, knowledge-driven paradigm. The applicability and effectiveness of the framework were demonstrated through a conceptual design case study of a household product. The results indicate that the proposed approach enhances the transparency and consistency of early-stage engineering decisions, reduces dependence on individual expertise, and provides an interpretable industrial intelligence solution for supporting knowledge-intensive engineering innovation.

Keywords: Industrial intelligence; Knowledge representation; Rule-based reasoning; Engineering decision support; Early-stage engineering innovation

1 Introduction

New product development is a critical pathway for achieving economic growth and improving market performance, and it has therefore attracted sustained attention from industrial research and development (R&D) practitioners. However, during the fuzzy front end of new product development, limited information availability and high design ambiguity are typically encountered, making effective innovation highly dependent on innovation methods and design elements, such as design data [1–3]. From an industrial systems perspective, the fuzzy front end of new product development should be regarded not merely as a design problem, but as a representative knowledge-intensive decision-making problem involving multiple cognitive and reasoning activities, including objective formulation, constraint identification, conflict analysis, and solution evaluation. Relevant information is often distributed across heterogeneous sources, characterized by structural diversity, and heavily dependent on tacit expert knowledge. As a result, early-stage innovation decision-making processes are difficult to standardize, reproduce, and share. Consequently, transforming engineering design activities into representable, inferable, and evaluable knowledge-processing and decision-support processes has become one of the key research topics in contemporary industrial intelligence.

Design data constitute a fundamental support for new product R&D. The importance of data (parameters) in the fuzzy front end of product development was emphasized by Park et al. [4], where a data-driven model was established to reduce uncertainty and ambiguity in parameter processing. Marion et al. [5] integrated artificial intelligence (AI) into the fuzzy front end of product development, enabling the identification of critical data insights and providing effective data support for designers. Innovation methodologies have also been shown to play a significant role in promoting product research and design. Yang et al. [6] addressed customer emotional requirements in environmentally friendly products and employed TRIZ to resolve contradictions embedded in these requirements. Yao et al. [7] applied TRIZ-based contradiction analysis and substance–field modeling to identify core problems in deep soft-rock roadway support. By drawing on TRIZ inventive principles such as pre-action and flexible shells, a fully enclosed steel shell–grid support technology was proposed, effectively controlling large surrounding-rock deformation and floor heave. This work expands the application scope of TRIZ in coal-mine roadway support and provides new insights for engineering optimization design. Liu et al. [8] proposed a product-integrated innovation design process model based on biological inspiration and further combined TRIZ to support concept generation and conflict resolution; the approach was validated through a robotic design case.

In addition, Hmina et al. [9] adopted wastewater screening and filtration system design as a case study and developed a structured innovation design support method based on TRIZ. Tools such as the contradiction matrix and scientific effects were applied during the conceptual design stage. The results demonstrated that the application of TRIZ significantly improved both conceptual novelty and design efficiency, providing empirical evidence and a practical framework for the systematic integration of TRIZ tools in engineering education. Yao et al. [10] applied the TRIZ method to innovative drainage cover design by employing the contradiction matrix to identify conflicts among engineering parameters and generating innovative solutions based on corresponding inventive principles. By integrating universal design principles and ergonomics, the design scheme was further optimized, resulting in improved usability and hygiene performance. Santoso et al. [11] conducted a redesign of a laparoscopic surgeon's chair using TRIZ as the core methodology, integrating functional analysis, causal chain analysis, and trimming techniques. Redundant components were eliminated through function-trimming, while contradictions between comfort and structural complexity were resolved using the contradiction matrix and separation principles. Deficiencies in comfort and functionality observed in existing designs were effectively addressed, validating the applicability of TRIZ in medical device conceptual design. Ismail et al. [12] employed TRIZ to redesign a C2L machine cone lifter used in highway construction. A functional analysis model was utilized to clarify component functions and interrelationships, while engineering contradiction analysis was applied to identify key conflicts. Solutions were generated based on TRIZ principles, leading to a redesigned cone lifter that achieved a balance among lifting efficiency, structural durability, and cone integrity. Experimental testing demonstrated improved equipment reliability and operational safety, thereby confirming the effectiveness of TRIZ in resolving engineering contradictions and optimizing transportation infrastructure equipment.

The integration of multiple innovation methodologies has been shown to play a critical role in addressing challenges encountered in the fuzzy front end of new product development, thereby substantially improving the efficiency of innovative product design. Jiang et al. [13] investigated the interrelationships between TRIZ and Extenics and proposed an integrated innovation design approach in which both methods were jointly applied to product design, resulting in a marked improvement in innovation problem-solving efficiency.Xu and Chen [14] integrated life cycle design (LCD), the analytic hierarchy process (AHP), and TRIZ to propose the "LCD–AHP–TRIZ" method, which was applied to the design of an intelligent dehumidifier. Through this approach, low-carbon design requirements were systematically identified and innovation problems were effectively resolved, providing a scientific strategy for the sustainable development of intelligent products. Chen et al. [15] combined substance–field analysis from TRIZ with Extenics-based innovation methods and proposed a hybrid substance–field–Extenics innovation approach to guide product innovation design, leading to improved design efficiency. Yan et al. [16] integrated the Kano model, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method, and TRIZ to collect dual-category user requirements, classify requirement attributes, analyze interrelationships among requirements, and resolve design conflicts. This integrated approach was validated in the design of manicure tables and chairs, where contradictions between operational efficiency and customer experience were effectively addressed.

Furthermore, Lee et al. [17] combined the strengths of text mining, quality function deployment (QFD), and TRIZ to construct an integrated innovation design methodology and conducted a design practice for smart glasses. Customer requirements were extracted from online platforms using text mining techniques, translated into technical specifications through QFD, and resolved for technical conflicts using TRIZ, resulting in the design of sustainable smart glasses. Sarpong et al. [18] proposed a customer-driven innovation framework integrating AHP, QFD, and TRIZ for the design optimization of a cassava grater. Customer requirements were first identified and prioritized using AHP, subsequently translated into technical solutions via QFD, and finally resolved for technical contradictions using the TRIZ contradiction matrix, leading to an innovative design solution. Song et al. [19] proposed an integrated innovation design method combining user behavior analysis, fuzzy failure mode and effects analysis (FMEA), and TRIZ, which was applied to the design of an upper-limb hemiplegia rehabilitation exoskeleton. Potential failure points during product use were identified using user journey mapping, failure risks were quantitatively evaluated and prioritized through fuzzy FMEA, and targeted innovative solutions were generated using the TRIZ contradiction matrix and inventive principles. Chaiyachet et al. [20] developed a systematic method integrating two-phase QFD with TRIZ, in which user requirements such as safety and operational space were translated into ranked technical requirements through QFD, and technical contradictions were resolved using TRIZ. Design solutions, including material selection, screw modification, and the addition of permanent magnets, were proposed, demonstrating the effectiveness of QFD–TRIZ integration in balancing user needs and technical feasibility in medical device innovation.

In addition, Vern et al. [21] addressed structural optimization challenges arising from material substitution in the lower-door component of a two-stroke marine engine piston by integrating TRIZ with multi-criteria decision-making methods. Design contradictions were identified using TRIZ, and biologically inspired structures, such as those of the Amazon water lily, were referenced to generate design alternatives. AHP was employed to determine the weights of evaluation criteria, including stress and deformation, while the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was used for multi-criteria decision ranking to identify the optimal design. The results indicated reductions in both stress and deformation, validating the effectiveness of multi-method integrated innovation approaches. Chen et al. [22] constructed an innovation method integrating the Kano model, AHP, and TRIZ for the design of willow furniture. User requirements were classified using the Kano model, comprehensive weights of design factors were calculated using AHP to ensure alignment between design objectives and user needs, and engineering challenges encountered during the design process were identified and resolved using the TRIZ contradiction matrix. Al-Dwairi et al. [23] proposed an integrated QFD–TRIZ methodology for innovative product design, in which the analytical House of Quality was extended to reveal conflicting design parameters and generate resolution strategies, providing a systematic framework for innovation planning and solution development. Gui et al. [24] proposed a requirements–function–principle–structure (RFPS) model integrating Extenics and TRIZ. During product redesign, top-level requirements were mapped to functional, principle, and structural requirements using Extenics analysis, while TRIZ was employed to resolve design problems encountered during the process. The applicability of the model was demonstrated through the innovative design of a cutting table. Turkan [25] applied the TRIZ contradiction matrix to the innovative design of a liquid-cooled radiator for electric vehicles. Inventive principles such as segmentation and parameter change were used to propose innovative directions involving fin shape, quantity, and inlet length. The Taguchi method was further applied to perform multi-objective optimization of key parameters, leading to the determination of an optimal design combination. Muhammad et al. [26] addressed functional challenges in the lifting mechanism of an unmanned aerial vehicle (UAV) take-off and landing station by integrating TRIZ functional analysis and engineering contradiction analysis. Through functional analysis, the functions and interrelationships of system components were systematically identified, and the lifting mechanism subsystem was explicitly defined. Engineering contradictions associated with three lifting solutions—mechanical, hydraulic, and pneumatic—were subsequently analyzed. A mechanical lifting mechanism was ultimately selected, enhancing the functionality and reliability of the UAV station and validating the effectiveness of combined TRIZ tools in resolving engineering contradictions.

From the perspective of industrial intelligence and intelligent systems, the aforementioned studies, although rich in methodological contributions, have largely remained at the level of tool integration and process design. Systematic modeling of engineering knowledge representation, reasoning mechanisms, and decision consistency has generally been lacking. In other words, a unified intelligent framework capable of transforming engineering problems into structured knowledge and supporting decision-making through interpretable reasoning mechanisms has not yet been established. This limitation has, to some extent, constrained the scalability and deployability of existing methods in complex industrial scenarios.

The reviewed studies demonstrate that design data, innovation methods, and their integration play an important role in product R&D; however, several notable limitations persist. In multi-method integration studies, differences among innovation tools and theoretical systems often lead to inconsistencies in innovation logic, while manufacturing constraints have not been systematically incorporated. Moreover, existing integrations of TRIZ and Extenics have primarily focused on isolated stages of the design process, rather than forming a closed-loop framework covering the entire lifecycle. In addition, solution evaluation criteria have frequently been selected based on experience, without explicit linkage to laws of product technological evolution. Consequently, comprehensive consideration of design data derived from user requirements and manufacturing constraints, the application of integrated innovation methods for conflict resolution, and systematic product solution evaluation remain worthwhile research directions.

Based on the above analysis, innovation design methods should be restructured from the perspective of industrial intelligent systems and reconceptualized as knowledge representation and reasoning frameworks oriented toward engineering innovation, rather than being treated merely as design workflows or tool combinations. To address these challenges, a full-element product design method integrating Extenics and TRIZ was proposed. By overcoming the localized and fragmented limitations of existing hybrid approaches, the proposed method takes Extenics-based innovation theory and TRIZ as its core, deeply coupling the formal descriptive capability of Extenics basic-elements with TRIZ-based conflict resolution and evolution laws. Innovation tools, including basic-element models, substance–field coupling models, TRIZ product evolution laws, and goodness evaluation methods, are systematically integrated. Through this framework, product innovation designers are supported across the entire process of "user requirements–product objectives–manufacturing constraints–conflict resolution–solution evaluation." Three core challenges are addressed in a coordinated manner: formal transformation of requirements, generation of feasible solutions under constraints, and lifecycle adaptability of design solutions. As a result, product innovation solutions that simultaneously achieve feasibility and adaptability are obtained, significantly enhancing innovation efficiency. Furthermore, by explicitly formalizing engineering knowledge structures and reasoning pathways, the proposed framework contributes to improved transparency, interpretability, and consistency in decision-making processes, thereby providing a foundational basis for subsequent system integration and digital deployment.

2 Full-Element Framework for Product Innovation Design

Product innovation design is generally conducted in accordance with established innovation processes, which typically involve the acquisition and analysis of user requirements, consideration of manufacturing processes, and optimization and selection of design solutions. The data utilized throughout these stages are regarded as elements. Accordingly, the full-element framework for product innovation design is composed of three primary components: product objectives, manufacturing constraints, and solution maturity indicators, as illustrated in Figure 1.

Figure 1. Three elements of product innovation design

2.1 Product Objectives

Product objectives constitute the core of product innovation design. Product objectives are defined with user requirements as the primary orientation and serve to specify product functions capable of satisfying those requirements. User requirements are commonly classified into functional requirements and affective requirements [23, 24]. Taking a dishwasher as an illustrative example, requirements related to improving cleaning efficiency or expanding cleaning functions, such as sterilization, are categorized as functional requirements. In contrast, requirements concerning compact size, lightweight structure, and minimal space occupation are classified as affective requirements. Correspondingly, product objectives may be divided into functional objectives and affective objectives based on the categorization of user requirements.

2.2 Manufacturing Constraints

Product manufacturing processes are required to be adjusted in accordance with product objectives; therefore, corresponding adjustments to manufacturing constraints must be considered. Manufacturing constraints are decomposed into three fundamental elements: enterprise production management, manufacturing equipment required for product modification, and the product modification object.

A composite basic-element model is first employed to represent the three elements of manufacturing constraints [8]. In Extenics, the basic-element model is a modeling tool used to represent objects, actions, and relationships. Its general expression is given as $B = (O, C, V)$, where O denotes the object being described, C represents a characteristic, and V corresponds to the quantitative value of that characteristic. In a composite basic-element model, one or more matter-element values M associated with the characteristics are typically included. Accordingly, a composite affair-element $A_v(M_j)$ is used to represent enterprise production management, while composite matter-elements $M_s(M_j)$ and $M_o(M_j)$ are employed to represent manufacturing equipment and the product modification object, respectively:

$$A_v(M_j) = \begin{bmatrix} O_v, & c_{v1}, & v_1 \\ & \vdots & \vdots \\ & c_{v_i}, & M_j \\ & \vdots & \vdots \\ & c_{v_n}, & v_n \end{bmatrix} \tag{1}$$

$$M_s(M_j) = \begin{bmatrix} O_s, & c_{s1}, & v_1 \\ & \vdots & \vdots \\ & c_{s_i}, & M_j \\ & \vdots & \vdots \\ & c_{s_n}, & v_n \end{bmatrix} \tag{2}$$

$$M_o(M_j) = \begin{bmatrix} O_o, & c_{o1}, & v_1 \\ & \vdots & \vdots \\ & c_{o_i}, & M_j \\ & \vdots & \vdots \\ & c_{o_n}, & v_n \end{bmatrix} \tag{3}$$

The above representation is further integrated with the substance–field model from TRIZ. In the TRIZ framework, a substance–field model describes the interaction in which a field F acts on a substance S_1, thereby enabling S_1 to act on another substance S_2. Within the context of manufacturing constraints, production management, manufacturing equipment, and the modification object correspond to the field F, substance S_1, and substance S_2, respectively.

By integrating the composite basic-element model with the substance–field model, a substance–field model for manufacturing constraints is obtained, as illustrated in Figure 2.

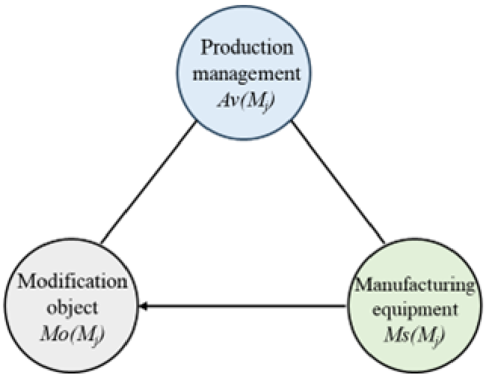

Figure 2. Substance–field model of manufacturing constraints

In this model, the composite affair-element A_v represents production management throughout the product manufacturing and modification process. The modification object M_o denotes the entity subjected to processing or transformation by the manufacturing equipment M_s, such as materials or components. For these three categories of to-be-resolved substance–field models, TRIZ provides six general solution types for addressing practical problems, as summarized in Table 1.

Table 1. Six general solution types for substance–field models

Solution Type	Applicable Model Type	Specific Measures
General solution 1	Incomplete model	Supplement missing elements (e.g., field F or substance S)
General solution 2	Harmful-effect model	Introduce a third substance S_3 to block or eliminate effects
General solution 3		Introduce an additional field F_2 to counteract the effect
General solution 4	Insufficient-effect model	Replace the original field with another field F_2
General solution 5		Introduce an additional field F_2 to enhance the desired effect
General solution 6		Introduce S_3 with F_2 to strengthen the required effect

2.3 Solution Maturity Indicators

The final step of product innovation design involves the evaluation and selection of design solutions. Solution maturity indicators constitute the key elements for effective solution evaluation and selection. Solution maturity indicators are derived based on the eight laws of technological evolution in TRIZ. These laws were formulated through systematic analysis of recurring patterns in the evolution of technical systems and are used to guide the direction of product innovation design. The complete evolution cycle of a product is typically divided into four stages: infancy, growth, maturity, and decline. Each development stage is associated with specific technological evolution laws. Accordingly, appropriate laws are selected as solution maturity indicators based on the current development stage of the product, as summarized in Table 2.

The selection of solution maturity indicators provides guidance for the subsequent construction of solution goodness evaluation metrics, ensuring that solution assessment is aligned with the actual technological development stage of the product.

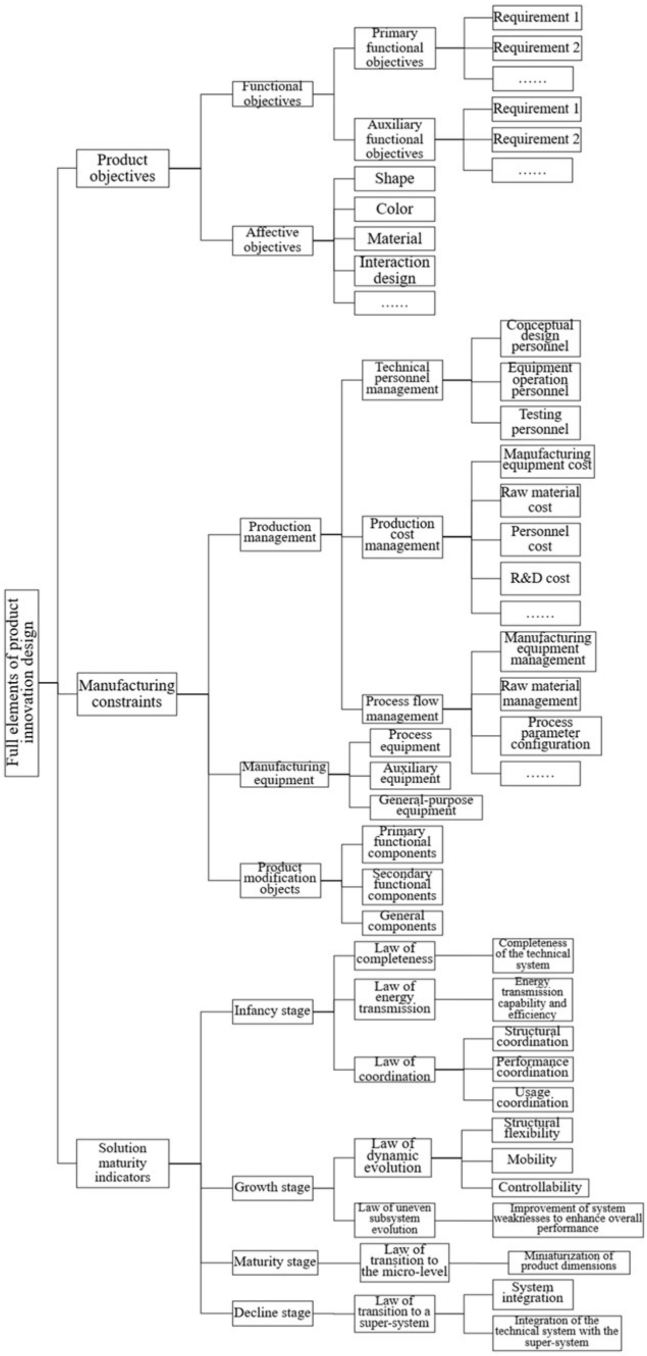

Figure 3. Data structure for product design

Table 2. Evolution laws and characteristics corresponding to different product development stages

Product Development Stage	Law of Technological Evolution	Characteristics of the Law
Infancy	Law of completeness	Completeness of the technical system
	Law of energy transmission	Energy transmission capability and efficiency
Growth	Law of coordination	Structural, performance, and usage coordination
	Law of dynamic evolution	Structural flexibility, mobility, and controllability
	Law of uneven subsystem evolution	Improvement of system weaknesses
Maturity	Law of transition to the micro-level	Miniaturization of product dimensions
Decline	Law of transition to a super-system	System integration and merging

2.4 Full-Element Data Structure for Product Innovation Design

To facilitate the application of programming-based approaches by R&D personnel in product innovation design, the full-element components—namely product objectives, manufacturing constraints, and product solution evaluation—are further decomposed into structured data representations. The corresponding full-element data structure for product innovation design is illustrated in Figure 3.

3 Product Design Method Oriented Toward Full-Element Innovation Design

Taking the full elements of product innovation design as inputs, a product design method oriented toward full-element innovation design was established. The method consists of the following three main steps:

3.1 Construction of the Product Objective Basic-Element Model

Product objectives are described using the composite affair-element model derived from Extenics basic-element theory. For product objectives, a composite basic-element model integrating affair-elements and matter-elements is constructed, forming an n-dimensional affair-element $A_{ui}(M_j)$ that contains matter-elements M_j:

$$A_{ui}(M_j) = \begin{bmatrix} O_{ui}, & c_{ui1}, & v_{ui1} \\ & \vdots & \vdots \\ & c_{uij}, & M_j \\ & \vdots & \vdots \\ & c_{uin}, & v_{uin} \end{bmatrix} \tag{4}$$

where, $M_j = (o_j, c_j, v_j)$ denotes the quantitative value of the matter-element corresponding to the characteristic c_{uij}. In general, one or more matter-element values M associated with different characteristics are included in the composite basic-element model A_u of product objectives.

Taking a dishwasher as an illustrative example, the product objective corresponding to the requirement of accommodating more tableware during multi-person dining scenarios is expressed using a composite affair–matter basic-element model as follows:

$$A(M_j) = \begin{bmatrix} \text{put inside}, & \text{target object}, & M_{u11} \\ & \text{scenario}, & \text{multi-person dining} \end{bmatrix} \tag{5}$$

The matter-elements M_j contained in the composite basic-element model $A(M)$ are given by:

$$M = \begin{bmatrix} \text{tableware}, & \text{type}, & \text{plates} \\ & & \text{bowls} \\ & & \text{pans} \\ & & \text{basins} \\ & & \text{seasoning dishes} \end{bmatrix} \tag{6}$$

3.2 Resolution of Design Conflicts

During the conceptual design stage, innovative product functions are frequently found to conflict with existing product parameters. For example, an increase in functional capability may result in larger spatial occupation, while improvements in operational efficiency may lead to increased power consumption. To address such conflicts, conflict resolution is conducted using the TRIZ contradiction matrix and inventive principles. In the contradiction matrix, parameters to be improved and parameters that may deteriorate are treated as matrix variables. After the improvement and deterioration parameters are identified for a given product, corresponding inventive principles provided by the matrix are applied to guide innovative design solutions.

3.3 Solution Goodness Evaluation

Based on the solution maturity indicators defined within the product solution evaluation elements, corresponding solution goodness evaluation criteria are generated. The goodness evaluation method from Extenics innovation theory, which is a fundamental approach for assessing the superiority or inferiority of solutions, is employed to evaluate product design alternatives. Through this process, the optimal product innovation design solution is ultimately selected.

The goodness evaluation procedure consists of the following steps:

Step 1: Determination of evaluation indicators

According to the requirements of the specific product problem, evaluation indicators for solution assessment are defined as MI:

$$MI_i = (c_i, V_i) \tag{7}$$

where, c_i denotes the evaluation characteristic, and V_i represents the quantitative value of that characteristic.

Step 2: Assignment of weight coefficients α and construction of correlation functions

After the evaluation indicators are selected, weight coefficients α are assigned according to the relative importance of each indicator. Correlation functions $k_i(o_j)$ are then constructed to determine the degree of association between a product solution and each evaluation indicator.

Step 3: Calculation of normalized correlation degree

Let the correlation degree of solution Q_i with respect to evaluation indicator MI_i be denoted as $k_i(o_j)$. The corresponding normalized correlation degree $g_i(O_j)$ is calculated as:

$$g_i(O_j) = \frac{k_i(o_j)}{\max_{1\leq j\leq n} |k_i(o_j)|} \tag{8}$$

Step 4: Calculation of solution goodness $C(Q_i)$

Finally, the solution goodness for each design alternative is calculated using the goodness evaluation formula below. The solution with the highest goodness value is identified as the optimal solution.

$$C(O_j) = \sum_{i=1}^{n} \alpha_i \cdot g_i(O_j) \tag{9}$$

3.4 Full-Element Product Design Process

The complete process of product innovation design under the full-element framework is illustrated in Figure 4. By applying the full-element-oriented product design method, innovative design solutions are generated through the following stages:

Stage 1: Element input stage

Three core elements are taken as inputs: (a) product objective elements, encompassing both user functional requirements and affective requirements; (b) manufacturing constraint elements, including production management specifications, manufacturing equipment parameters, and process technology requirements; (c) solution maturity indicator elements, which are extracted in accordance with TRIZ laws of technological evolution by considering the product's technological lifecycle stage.

Stage 2: Innovative solution generation stage

Based on Extenics basic-element theory, product objectives are formalized using a matter–affair composite model, through which a clear and inferable product objective model is constructed. Technical or physical contradictions between the product objective model and manufacturing constraints are identified. Technical contradictions are addressed by consulting the TRIZ contradiction matrix to match corresponding inventive principles, whereas physical contradictions are resolved using TRIZ separation principles to formulate solution strategies. On this basis, multiple candidate solutions that satisfy both requirements and constraints are generated.

Stage 3: Solution screening stage

An Extenics-based goodness evaluation indicator system is established, incorporating functional adaptability, constraint satisfaction, and technological maturity. Indicator weight coefficients are determined, and goodness values of candidate solutions are calculated using Extenics correlation functions. Finally, candidate solutions are ranked according to their goodness values, and the optimal solution is selected to complete the closed-loop design process.

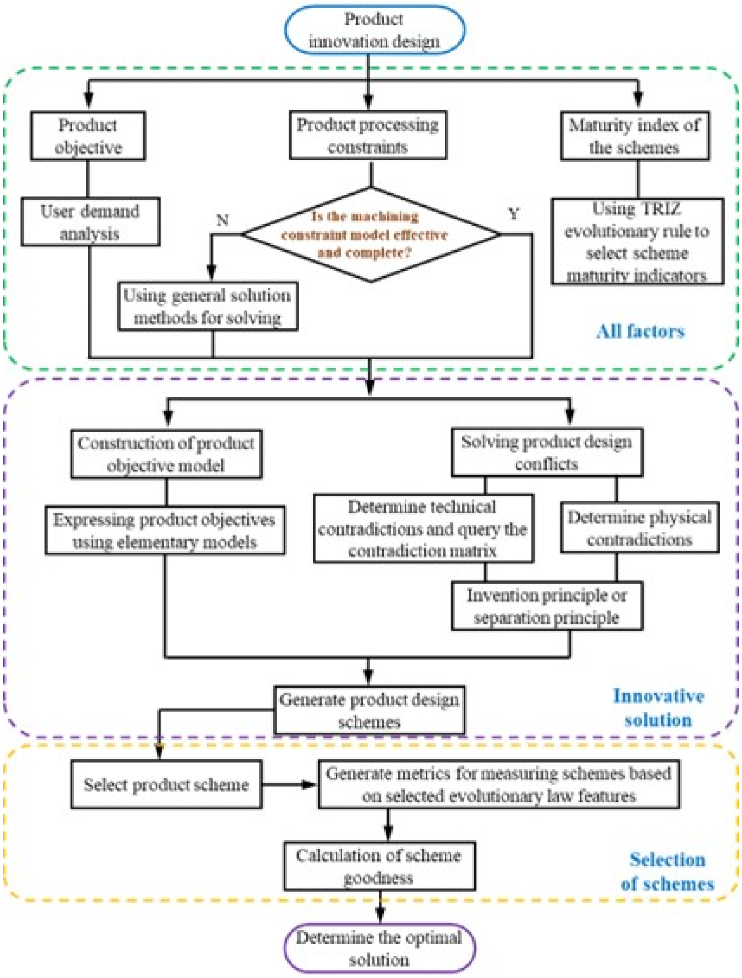

Figure 4. Full-element-oriented product innovation design process

4 Design Case Study

A household dishwasher was selected as the illustrative case, as shown in Figure 5 and Figure 6. The dishwasher has overall dimensions of 650 mm × 500 mm × 400 mm and is capable of accommodating 12 plates, 12 bowls, 12 pairs of chopsticks and spoons, one frying pan, as well as additional seasoning dishes.

Using this dishwasher as the design object, product innovation design was conducted based on the diamond model.

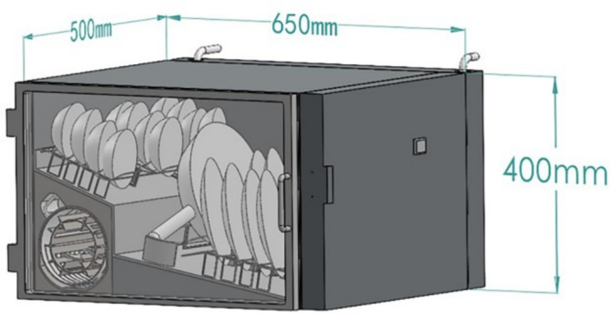

Figure 5. Household dishwasher used for the case study

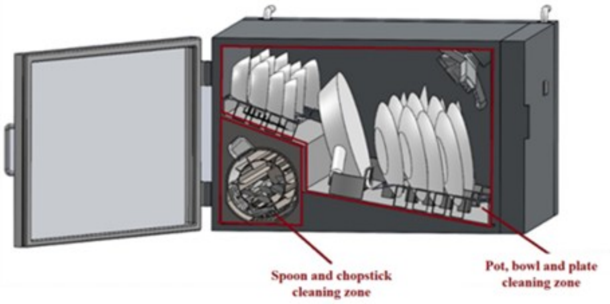

Figure 6. Schematic illustration of dishwasher cleaning zones

4.1 Innovation Design Elements

4.1.1 Product objectives

Expert consultation was conducted with specialists from a household appliance brand, through which user requirements for the dishwasher were identified as follows:

Requirement 1: When tableware is placed into the dishwasher, residual liquids such as food juices may drip from the tableware and spill outside the dishwasher. Therefore, the problem of liquid dripping from tableware during placement is required to be addressed.

Requirement 2: During the cleaning process inside the dishwasher, food residues may be washed by water flow and accumulate at the bottom of the appliance, thereby obstructing water circulation and hindering the normal recycling of washing water. Consequently, the dishwasher is required to enable effective residue collection during cleaning while ensuring separation between residues and circulating water.

Through analysis of the above user requirements, both Requirement 1 and Requirement 2 were identified as functional requirements of the dishwasher. Accordingly, the corresponding product objectives were classified as functional objectives.

4.1.2 Manufacturing constraints

Based on the analysis of the identified requirements, different product components were selected as modification objects. For Requirement 1, the tableware-loading inlet door assembly of the dishwasher was selected as the modification object. For Requirement 2, the dishwasher washing system components were selected as the modification objects.

For innovative modifications to the dishwasher, factors such as raw material supply, manufacturing processes, and technical personnel in the production stage are required to be updated or adjusted. Accordingly, the manufacturing-constraint substance–field model of the dishwasher innovation was initially defined as an ineffective incomplete system, as illustrated in Figure 7.

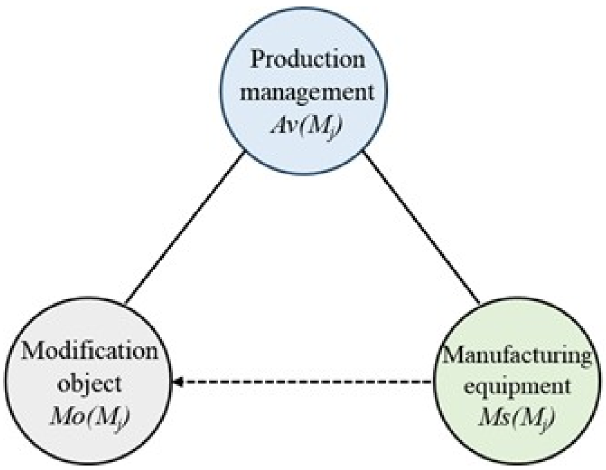

Figure 7. Ineffective incomplete system of manufacturing constraints

According to the solution approach for insufficient-effect models listed in Table 1, production management A_v within the manufacturing constraints was adjusted, and manufacturing equipment M_s was correspondingly modified, such that the manufacturing-constraint substance–field model was transformed into an effective complete system.

Within this substance–field model, production management $A_v(M_j)$ (field F), manufacturing equipment $M_s(M_j)$ (substance S_1), and modification object $M_o(M_j)$ (substance S_2) are represented using basic-element models, as described below.

$$A_v = \begin{bmatrix} \text{dishwasher product,} & c_{v1}, & \{\text{production equipment, raw materials, parameters...}\} \\ & c_{v2}, & \{\text{raw material procurement, manufacturing equipment cost...}\} \\ & sc_{v3}, & \{\text{R\&D design personnel, operators, testing personnel...}\} \end{bmatrix} \tag{10}$$

$$M_s = \begin{bmatrix} \text{dishwasher mfg. equip.,} & c_{s1}, & \{\text{forming, processing, testing equipment...}\} \\ & c_{s2}, & \{\text{conveying, robotic automation equipment...}\} \\ & c_{s3}, & \{\ldots\} \end{bmatrix} \tag{11}$$

$$M_o = \begin{bmatrix} \text{dishwasher components,} & c_{o1}, & \{\text{door opening direction, door opening mode...}\} \\ & sc_{o2}, & \{\text{installation position, washing method...}\} \end{bmatrix} \tag{12}$$

An active transformation was applied to the production management element A_v, through which management adjustments were implemented in the production process flow, production cost control, and technical personnel training associated with the dishwasher manufacturing process. As a result, the manufacturing-constraint substance–field model was transformed from an ineffective incomplete system into an effective complete system, as illustrated in Figure 8.

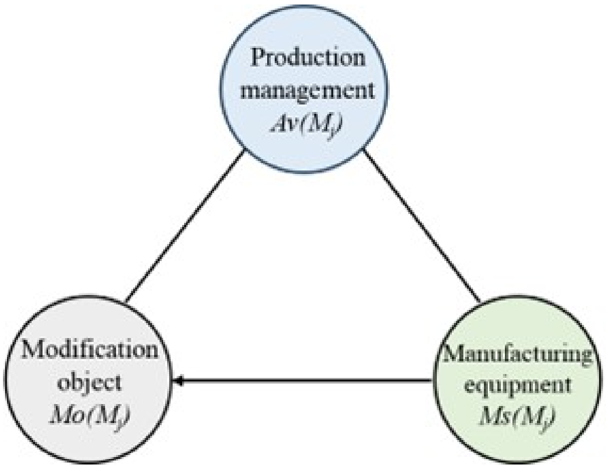

Figure 8. Effective complete system of manufacturing constraints

4.1.3 Solution maturity indicators

An analysis of performance parameters and technological maturity levels of dishwasher products was conducted based on relevant domestic literature [27, 28]. The results indicate that, among the various dishwasher components, the inlet door assembly remains at the infancy stage of technological development, whereas the washing system components have reached the growth stage. Accordingly, for the inlet door assembly, the law of coordination was selected as the corresponding solution maturity indicator, while for the washing system components, the law of uneven subsystem evolution was selected. Based on Table 2, the characteristic attributes of the law of coordination and the law of uneven subsystem evolution are identified as structural coordination, performance coordination, usage coordination, and improvement of system weaknesses to enhance overall performance, respectively. These attributes were adopted as the basis for selecting evaluation criteria in the subsequent solution goodness assessment.

4.2 Construction of the Product Objective Basic-Element Model

User requirements contained in the product objective elements were transformed into functional objectives and represented using the composite affair-element model A_n:

Functional Objective 1

$$\begin{cases} A_{u1} = \begin{bmatrix} \text{contain,} & \text{target object,} & M_{u11} \\ & \text{scenario,} & \text{during tableware loading} \end{bmatrix} \\ M_{u11} = (\text{tableware food liquid, fluidity, viscous}) \end{cases} \tag{13}$$

Functional Objective 2

$$\begin{cases} A_{u2} = (\text{recover, target object}, M_{u31}) \\ A_{u3} = \begin{bmatrix} \text{separate,} & \text{receiving object,} & M_{u31} \\ & \text{receiving object,} & \text{residue–water mixture} \end{bmatrix} \\ M_{u21} = M_{u31} = (\text{tableware residue, property, solid–liquid mixture}) \end{cases} \tag{14}$$

4.3 Design Conflict Resolution and Solution Generation

The functional objectives derived from user requirements were analyzed to identify corresponding modification objects. For Functional Objective 1, the dishwasher inlet assembly was selected as the modification object. For Functional Objective 2, the dishwasher washing system components were selected as the modification objects.

For Functional Objective 1, the issue can be addressed by adding a component at the inlet to collect food liquids dripping from tableware during loading. As a result, the applicability and versatility of the dishwasher are improved; therefore, the improving parameter was selected as Engineering Parameter 35 (adaptability and versatility). However, the increase in components leads to higher structural complexity, and thus the worsening parameter was selected as Engineering Parameter 36 (device complexity). For Functional Objective 2, modification of the washing components enables improved cleaning efficiency and increased washing speed. Accordingly, the improving parameter was selected as Engineering Parameter 9 (speed). However, this improvement may result in increased power consumption; therefore, the worsening parameter was selected as Engineering Parameter 21 (power). Based on the improving and worsening parameters identified for Functional Objectives 1 and 2, the corresponding inventive principles were selected by consulting the TRIZ contradiction matrix, as summarized in Table 3.

Table 3. Functional conflict models of the manufacturing constraint system

Conflict	Improving Parameter	Worsening Parameter	Inventive Principles
Functional objective 1	35. Adaptability and versatility	36. Device complexity	15. Dynamization 29. Pneumatic and hydraulic structures 37. Thermal expansion 28. Replacement of mechanical systems
Functional objective 2	9. Speed	21. Power	19. Periodic action 35. Transformation of material properties 38. Strong oxidation 2. Extraction (extracting part of the water from the pump to the newly added rinsing component)

For the conflict associated with Functional Objective 1, Inventive Principle 28 (replacement of mechanical systems) was selected. By redesigning the dishwasher inlet assembly, the inlet component is repurposed as a substitute for a dedicated food-liquid collection component. For the conflict associated with Functional Objective 2, Inventive Principle 19 (periodic action) was selected. By introducing an additional rinsing component with periodic operation, food residues accumulated at the bottom of the dishwasher are flushed intermittently, thereby accelerating residue recovery efficiency.

4.4 Solution Generation and Goodness Evaluation

After problem-solving was conducted for the manufacturing constraints and design conflicts, innovative design solutions for the dishwasher door-opening mechanism and the internal washing device were generated by integrating the selected inventive principles with the effective complete manufacturing-constraint system. The resulting product design solutions are summarized in Table 4.

Guided by the solution maturity indicators defined in the innovation design elements—specifically, the characteristics of the law of coordination and the law of uneven subsystem evolution—evaluation criteria were established below.

For Solutions O1 and O2, which involve modifications to the dishwasher inlet assembly, the law of coordination was adopted as the guiding maturity indicator. Accordingly, usage coordination was selected as evaluation indicator MI_1, and liquid drip-prevention performance was selected as evaluation indicator MI_2. For Solutions O3 and O4, which involve modifications to the dishwasher washing system components, the law of uneven subsystem evolution was adopted as the guiding maturity indicator. Accordingly, functional completeness was selected as evaluation indicator MI_3, and rinsing and residue recovery efficiency was selected as evaluation indicator MI_4.

In addition, process feasibility was introduced as evaluation indicator MI_5. On this basis, the goodness values of all candidate solutions were calculated to enable comparative evaluation and selection of the optimal product innovation design solution.

Table 4. Product design solutions

Product Objective	Design Solution A	Design Solution B
Functional objective 1	Solution O1: Dripping of food liquids during tableware loading is prevented by replacing the left-opening door with a pull-down door.	Solution O2: Dripping of food liquids during tableware loading is prevented by replacing the left-opening door with a top-opening door.
Functional objective 2	Solution O3: Residues washed from tableware are cleaned and recovered by adding water-spray nozzles that use water jets.	Solution O4: Residues washed from tableware are cleaned and recovered by adding air-flow nozzles that use gas streams.

Step 1: Determination of evaluation indicators

By integrating the characteristics of the selected laws, five evaluation indicators were defined for the goodness evaluation method, namely MI_1, MI_2, MI_3, MI_4, and MI_5:

$$MI_1 = (\text{usage coordination}, V_1) \tag{15}$$
$$MI_2 = (\text{liquid drip–prevention performance}, V_2) \tag{16}$$
$$MI_3 = (\text{functional completeness}, V_3) \tag{17}$$
$$MI_4 = (\text{rinsing and residue recovery efficiency}, V_4) \tag{18}$$
$$MI_5 = (\text{process feasibility}, V_5) \tag{19}$$

where, V_i $(i = 1, 2, 3, 4, 5)$ denotes the quantitative value of each evaluation indicator.

Step 2: Determination of weight coefficients α

AHP was employed to determine the weight coefficients of the evaluation indicators used in the goodness assessment. Pairwise comparisons of the relative importance among the five indicators were conducted, and the resulting result is presented in Table 5.

Table 5. Evaluation indicator comparison

Indicator 1 / Indicator 2	Usage Coordination / Functional Completeness	Liquid Drip-Prevention / Rinsing Recovery Efficiency	Process Feasibility
Usage coordination / Functional completeness	1	2/3	2
Liquid drip-prevention / Rinsing recovery efficiency	3/2	1	2
Process feasibility	1/2	1/2	1

Using the AHP geometric mean (root) method, the weight coefficients of the five evaluation indicators were obtained as follows: $\alpha_1 = \alpha_3 = 0.35$, $\alpha_2 = \alpha_4 = 0.45$, and $\alpha_5 = 0.2$.

Step 3: Construction of correlation functions and calculation of correlation degrees

For the dishwasher case, the five evaluation indicators—usage coordination, liquid drip-prevention performance, functional completeness, rinsing and residue recovery efficiency, and process feasibility—were each discretized into five ordinal levels, with 5 representing the optimal level and 1 representing the poorest level. On this basis, discrete correlation functions $k_i(x)$ $(i = 1, 2, 3, 4, 5)$ were established as follows:

$$k_i(x) = \begin{cases} 2, & x = \text{relatively convenient / relatively good / relatively high / relatively simple} \\ 1, & x = \text{convenient / good / high / simple} \\ 0, & x = \text{moderate} \\ -1, & x = \text{inconvenient / poor / low / complex} \\ -2, & x = \text{relatively inconvenient / relatively poor / relatively low / relatively complex} \end{cases} \tag{13}$$

For Functional Objective 1, Solution O1 replaces the left-opening door with a pull-down door. As a result, liquid dripping during tableware loading is effectively avoided, while opening and closing operations remain convenient and user-friendly. Accordingly, the value was assigned as $k_{c1}(O_1) = 1$. In addition, the pull-down door can collect food liquids beneath the tableware during loading; however, its drip-prevention performance is moderate. Since the manufacturing process is relatively simple and does not adversely affect the overall dishwasher structure, the values were assigned as $k_{c2}(O_1) = 0$ and $k_{c5}(O_1) = 1$. Solution O2 replaces the left-opening door with a top-opening door. Although liquid dripping is similarly prevented, top-loading operation is relatively inconvenient in practice. Therefore, the value was assigned as $k_{c1}(O_2) = -2$. While drip-prevention performance is superior to that of the pull-down door, the associated manufacturing process is more complex. Consequently, the values were assigned as $k_{c2}(O_2) = 2$ and $k_{c5}(O_2) = -2$.

For Functional Objective 2, Solution O3 employs water-jet flushing to collect residues washed from tableware. This solution requires only the addition of several water-spray nozzles inside the dishwasher. The approach effectively compensates for functional shortcomings in the washing subsystem, enhances overall functionality, and significantly improves rinsing and residue recovery efficiency. Accordingly, the values were assigned as $k_{c3}(O_3) = 2$ and $k_{c4}(O_3) = 1$. Since the required manufacturing process is relatively simple, $k_{c5}(O_3) = 1$ was assigned. Solution O4 employs airflow-based cleaning to recover residues washed from tableware. Similar to Solution O3, functional deficiencies are addressed and recovery efficiency is improved. However, this solution requires the installation of internal fans, resulting in higher energy consumption compared with water-jet flushing. Therefore, the values were assigned as $k_{c3}(O_4) = 2, k_{c4}(O_4) = 1$, and $k_{c5}(O_4) = -1$.

Step 4: Calculation of normalized correlation degree

Using the normalized correlation degree formula given in Eq. (8), the normalized correlation degrees of the candidate solutions with respect to the evaluation indicators were obtained as follows: $g_1(O_1) = 1, g_1(O_2) = -1; g_2(O_1) = 0, g_2(O_2) = 1; g_5(O_1) = 1, g_5(O_2) = -1;$ $g_3(O_3) = 1, g_3(O_4) = 1; g_4(O_3) = 1, g_4(O_4) = 0.5; g_5(O_3) = 1, g_5(O_4) = -0.5;$

Step 5: Calculation of solution goodness

Based on the formula $C(O_j) = \sum_{i=1}^{n} \alpha_i \cdot g_i(O_j)$, the goodness value of each candidate solution was calculated and the resulting goodness values are summarized in Table 6.

Table 6. Results of solution goodness calculation

Evaluation Indicator	**Weight Coefficient**	**Correlation Degree** $k_i(O_j)$		**Normalized Correlation Degree** $g_i(O_j)$		**Correlation Degree** $k_i(O_j)$		**Normalized Correlation Degree** $g_i(O_j)$	
		Solution O1	**Solution O2**	**Solution O1**	**Solution O2**	**Solution O3**	**Solution O4**	**Solution O3**	**Solution O4**
MI_1	0.4	1	-2	1	-1	—	—	—	—
MI_2	0.4	0	2	0	1	—	—	—	—
MI_3	0.4	—	—	—	—	2	2	1	1
MI_4	0.4	—	—	—	—	1	1	0.5	0.5
MI_5	0.2	1	-1	1	-0.5	1	-1	0.5	-0.5
Goodness value		—	—	0.6	-0.1	—	—	0.7	0.5

Based on the comparison of the solution goodness values presented in Table 6, it is indicated that, for Functional Objective 1 and Functional Objective 2, Solution O1 and Solution O3 achieve superior goodness among the four candidate solutions. Accordingly, Solution O1 and Solution O3 were selected for innovative improvement of the dishwasher product. The resulting design configurations are illustrated in Figure 9 and Figure 10, respectively.

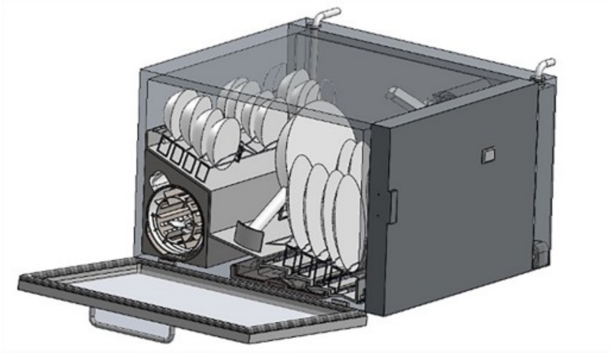

Figure 9. Dishwasher with a pull-down door configuration

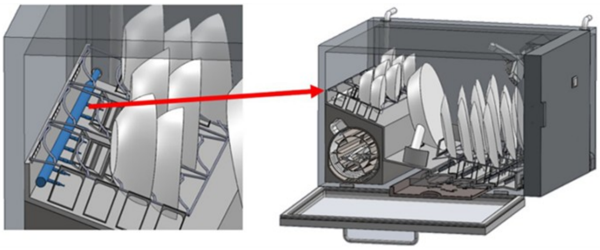

Figure 10. Additional water-spray nozzles installed at the upper-left region of the dishwasher

5 Conclusions

To address the information ambiguity and uncertainty inherent in the fuzzy front end of new product development, a full-element product innovation design method integrating Extenics and TRIZ was proposed. By systematically integrating three core categories of input elements—product objectives, manufacturing constraints, and solution maturity indicators—a structured framework and executable process for product innovation design were established. From the perspective of industrial intelligence, the proposed framework effectively constructs a mechanism for knowledge representation, reasoning, and decision support oriented toward the early stage of engineering innovation, thereby transforming innovation activities that traditionally rely on tacit experience into a knowledge-driven process that is representable, analyzable, and traceable. The main contributions and conclusions are summarized as follows:

- A full-element model for product innovation design was established. Three primary data sources driving fuzzy front-end innovation were explicitly identified. Product objectives and manufacturing constraints were formalized using Extenics composite basic-element models and TRIZ substance–field models, respectively, while TRIZ laws of technological evolution were adopted as evaluation guidance for solution maturity. Through this integration, a unified and standardized data representation foundation was formed. Such a unified representation facilitates the transformation of heterogeneous design information into structured engineering knowledge, thereby providing a processable basis for subsequent reasoning and decision-making.
- A full-element-oriented integrated design process was proposed. A three-stage execution process—element input, solution generation, and solution screening—was designed. The formal modeling advantages of Extenics were systematically combined with the contradiction-solving capability of TRIZ, enabling the innovation process to shift from experience-driven practices toward structured engineering. This process not only specifies the design steps but also characterizes how engineering knowledge is represented, transformed, and utilized at different stages, thereby providing a foundational structure for the future development of computable and deployable industrial intelligent systems.
- The feasibility and effectiveness of the method were validated through a household dishwasher design case. Using a dishwasher product as the case study, innovation design elements were constructed with explicit user requirements as guidance. Core needs related to liquid drip prevention and residue recovery were effectively addressed, resulting in more precise identification of design conflicts, significantly improved solution feasibility, and substantially enhanced innovation efficiency. The case results further demonstrate that the proposed framework improves the transparency and consistency of engineering decision-making, enabling relatively stable decision outcomes to be achieved by different engineers under similar constraint conditions.

The primary value of the proposed method lies in the provision of a systematic solution framework for the fuzzy front end of product innovation, and it is particularly suitable for incremental design scenarios in which objectives are explicit and constraints are well defined. Nevertheless, several limitations remain. Key stages, including substance–field model diagnosis, contradiction identification, and solution goodness evaluation, continue to rely on expert experience. The applicability of the method to large-scale and highly complex systems has yet to be fully validated, and subjective factors involved in the evaluation process require further control. From an industrial application perspective, the method demonstrates strong interpretability and engineering comprehensibility, facilitating integration with existing design workflows and information systems in enterprise R&D environments.

Future work will focus on the development of computer-aided innovation systems that support the proposed method and on exploring integration with AI technologies to reduce subjective dependence. In addition, the generality and scalability of the method will be further validated through a broader range of application cases. Particular emphasis will be placed on the co-design of knowledge modeling, rule-based reasoning, and human–computer interaction interfaces, with the aim of enhancing system usability and robustness in complex industrial environments.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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