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Multi-Criteria Decision-Making Approach for Design Evaluation and Optimization of Smart Pet Water Fountains

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Featured Application

The multi-criteria decision-making method introduced in this study is suitable for the product development processes of pet supply enterprises. By establishing an indicator system that considers the requirements of both humans and pets, this method enables quantitative evaluation and iterative optimization of smart pet water fountain designs. Furthermore, the approach can be extended to optimize the design of other smart pet products, such as feeders and litter boxes.

Abstract

To address the challenges of homogenization and unclear functional hierarchy in pet water fountain design, as well as to meet diverse user needs, reduce costs, and improve efficiency, this study undertakes product design based on comprehensive research and analysis of key design elements that fulfill the practical requirements of both humans and pets. Furthermore, to evaluate and optimize the proposed design scheme, an integrated AHP-improved CRITIC-TOPSIS comprehensive design evaluation model is introduced within the framework of multi-criteria decision theory to assess and refine pet water fountain design solutions. The methodology commences with the application of the AHP to construct a multi-level evaluation index system and determine subjective weights for each index. Subsequently, the improved CRITIC method is integrated to calculate the comprehensive weights of each indicator. The TOPSIS method is then employed to rank and optimize the design schemes. Strategies for further improvement are proposed based on key indicators that are assigned higher weights. The results of the simulation verification experiment and sensitivity analysis indicate that the proposed method achieves high accuracy and reliability in the evaluation of pet water fountain designs. This methodology establishes a rigorous evaluation framework that can be extended to other pet product designs.

Keywords: multi-criteria decision-making approach; analytic hierarchy process; pet water fountain; design evaluation; optimization model

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1. Introduction

The growth of the pet market and the increasing number of pet owners have driven diversification and technological progress in pet supplies. For example, advancements in artificial intelligence provide innovative opportunities for pet product design [1], improving both interactivity and safety. Contemporary product design and service concepts emphasize the physical and mental health of pets by considering material selection [2], operational safety, and the emotional and functional requirements of both humans and animals. This focus promotes comprehensive analysis of the human–pet relationship and aims to optimize user experience [3–5]. The design of pet water fountains, which are essential for modern pet owners, should address the needs of both humans and animals, functional structure, operational safety, and ease of use. The design of pet water fountains involves complex factors, including considerations related to users, animals, products, and environmental context. Despite the variety of pet water fountains available, product homogenization remains prevalent. The Analytic Hierarchy Process (AHP) [6,7] and multi-criteria decision-making methods [8,9] are widely applied to evaluate and support decision-making in complex product design systems. For example, Liang and Luo [10] applied the AHP method to optimize interactive pet toy design within pet product evaluation.

While the AHP-based evaluation method is recognized for its scientific rigor and broad applicability, it is limited by strong subjectivity, as a single subjective weight calculation may not accurately reflect the relative importance of various indicators. The comprehensive weighting method addresses this limitation by integrating statistical analysis with expert evaluation, incorporating the objective weighting method based on indicator correlation (CRITIC) into the subjective weighting process [11]. This integration achieves a unified approach to qualitative and quantitative analysis. The comprehensive weighting method is extensively used in industrial and product design evaluation [12–15], as it effectively balances expert subjective preferences with the influence of objective conditions on the indicator system. This enhances the systematic nature and accuracy of indicator weights, resulting in more scientific and reliable evaluation outcomes for complex systems. Furthermore, comprehensive evaluation methods that combine single or multiple weighting approaches with the ideal solution ranking method (TOPSIS) are prevalent in industrial production and broader societal applications [16]. AHP and the TOPSIS are primarily employed to rank customer needs [17]. For instance, reference [18] demonstrates the use of a combined AHP-TOPSIS approach to subjectively calculate and evaluate the ranking of design schemes for 3D printing products.

Previous studies have primarily concentrated on the qualitative evaluation of specific product functions or user experiences. However, it lacks a systematic evaluation framework that encompasses the progression from user needs to indicator development, quantitative analysis, and comprehensive evaluation. This gap is particularly evident in the context of pet products, which involve complex and multi-layered user requirements. The theoretical significance of this study is demonstrated by the integration of multiple multi-criteria decision-making methods into a systematic framework, as well as the introduction of a comprehensive evaluation approach that incorporates both subjective and objective factors into pet product design. This expands the application scenarios of multi-criteria decision-making theory and establishes a foundational methodology for the design of similar products. The practical significance of the proposed system is reflected in its capacity to accurately identify key indicators, thereby maximizing product efficiency, enhancing user experience, and offering a scalable design optimization method for the industry.

The main innovation of this article lies in the development of a complex indicator system that combines product analysis, pet drinking behavior analysis, and user research to meet needs at multiple levels. On the other hand, it combines the AHP method with the improved CRITIC method, which incorporates entropy-based redundancy information to accurately calculate the subjective and objective weights of each indicator. Additionally, integrating the TOPSIS method establishes a robust model for design evaluation and scheme optimization. To achieve the above goals, Section 2 analyzes the design elements of intelligent pet water fountains by examining comparable products and pet drinking behaviors.

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Section 3 investigates the evaluation system and process for design indicators of intelligent pet water fountains, utilizing the AHP method within the framework of multi-criteria decision theory. Section 4 examines the comprehensive design evaluation method and specific algorithm of an integrated AHP-CRITIC-TOPSIS approach. Section 5 utilizes the proposed method to evaluate and refine the product design scheme for intelligent pet water fountains. It also compares and validates the employed methods and resulting outcomes.

2. Design Element Analysis for Smart Pet Water Fountain

Recent statistics indicate that the proportion of households raising dogs and cats in China is relatively high, with both exceeding 50%. Currently, the number of cat-owning households significantly surpasses that of dog-owning households [19]. Furthermore, cats have greater requirements for drinking water, and cat owners demonstrate a stronger preference for purchasing pet water fountains. As a result, most pet water fountains available on the market are primarily designed for cats.

The design of pet water fountains should address not only the fundamental requirement of providing drinking water for pets but also incorporate user-centered considerations such as appearance, safety, energy efficiency, and intelligent control. Additionally, cost control is essential, as most consumers prioritize cost-effectiveness when making purchasing decisions. Several popular pet water fountains within the price range of 120 to 160 RMB were selected for product design analysis and evaluation. These products exhibit varying degrees of design improvements across different aspects, with each product emphasizing distinct features. Six pet product design experts and four pet owners participated in evaluating multiple aspects of each product. The mean ratings, summarized in Table 1, include "Safety rating", "Functionality rating", "Appearance rating" and "Interactivity rating." These items represent the average scores assigned by both evaluation experts and pet owners for safety, functionality, aesthetics, and interactivity, respectively.

Table 1. Design analysis and rating of competitive pet water fountain products.

Brand and Model	Price (RMB)	Design Highlights	Safety Rating	Functionality Rating	Appearance Rating	Interactivity Rating
Uah (Second Generation)	138.2	Wireless and external water pump; water and electricity separation; 0 electric charge	85	70	68	71
ETKIT SOLO2	158.0	Water and electricity separation, fully detachable and washable body, multiple purification	78	77	69	75
DONESS D03	121.6	Fountain flowing water, four-fold filtration, dry firing protection (operational safety), easy to clean	75	79	67	73
Xiaomi Mi-Home 2	128.0	Low noise and long battery life, large capacity, remote operation, easy to assemble	73	81	72	78
X'TANCHI Pet B03	136.0	304 stainless steel + ABS (material safety), unplugged (operational safety), low noise and long battery life, six-fold filtration, large capacity	82	80	70	70

Design analysis and rating results of comparable products demonstrate that market offerings prioritize enhancements in safety and functionality, with secondary emphasis on interactivity and appearance. This prioritization aligns with user requirements and expectations.

However, many pet products prioritize the experiential needs of pet owners [20], often neglecting pets' instinctive needs. The primary function of pet water fountains is to address pets' drinking and health needs, which necessitates comprehensive research on pet drinking behavior. This study integrates user and expert interviews and establishes a research group to conduct empirical observations aimed at understanding the characteristics of pet drinking behavior. Findings are summarized in terms of instinctive motivation, environmental barriers, and product-related barriers. The results indicate that product design should prioritize water promotion, visual appeal, low noise, ease of cleaning, and material safety, as detailed in Table 2.

Table 2. The correlation between research on pet drinking behavior and product design.

Analysis Perspective	Analysis of Drinking Behavior	Product Design Elements
Instinctual motivation	Flowing water preference: Cats and dogs are instinctively drawn to flowing water, which they perceive as cleaner and fresher. Water level perception: Cats tend to avoid containers that cause their whiskers to make contact with the sides; therefore, they prefer wide, shallow water containers.	Drinking water promotion
Environmental obstacles	Discomfort with drinking water: The impact force of the water flow is either excessive or insufficient. Visual impairment: The opacity of the sink impedes pets' ability to clearly observe the water level.	Modeling and appearance
	Fear of noise: Cats often exhibit fear responses to noises produced by water pumps and flowing water.	Low noise
Product obstacles	Hard-to-reach areas: Complex structures are susceptible to the accumulation of bacteria and biofilms, which may be detectable by pets.	Easy to clean
	Material odor: Low-quality plastic emits an odor that negatively influences individuals' willingness to consume water.	Material safety

Beyond addressing the needs of both humans and pets, the design of pet water fountains must also consider factors related to the product and its environment. Among the many design elements, it remains necessary to determine which are most critical, assess the relative importance of each, and identify the optimal design scheme for pet users. Addressing these questions requires developing a scientific, systematic evaluation framework. The process requires balancing and selecting among conflicting priorities for various design elements. Consequently, a scientific and rigorous evaluation system is required to objectively determine the relative importance of each design element and assess the overall design scheme. This approach ensures that user requirements and product functionality are effectively met.

Additionally, analysis of search indices and sales volumes on major e-commerce platforms in China indicates that pet water fountains priced between 120 yuan and 160 yuan are most popular. Consequently, the pet water fountain examined in this study is priced at approximately 150 yuan, with a price fluctuation not exceeding 20 percent. Under these circumstances, price is not considered a primary criterion for product design evaluation.

3. Indicator System Construction and Evaluation Process Under Multi-Criteria Decision Theory

The multi-criteria decision-making (MCDM) method, which integrates decision theory with systems methodology, addresses complex, ambiguous, and high-value systemic problems. MCDM offers a systematic and structured framework for resolving complex product design challenges by balancing objective factors and subjective needs [21–23]. In addition to user and product-related subjective and objective factors, the design of pet water fountains must also address the complexities of value diversity. Thus, it is essential to develop a comprehensive and multidimensional evaluation system within the multi-criteria decision-making framework. This system should incorporate subjective factors from pet users and objective factors from products and the environment, thereby establishing a more scientific and systematic indicator system and design evaluation method.

The development of a comprehensive indicator system is initiated through an analysis of pet drinking behavior, the requirements of both humans and pets, and pertinent product environmental factors using the Analytic Hierarchy Process (AHP) [24]. The AHP model organizes the content into a hierarchical structure comprising the objective layer, criterion layer, sub-criterion layer, and final solution layer. Firstly, we establish four criteria layers: functionality, safety, appearance, and interactivity, which correspond to the product design analysis, as shown in Table 1. Then, we identify key product design elements that address pet needs, including drinking promotion, size, low noise, ease of cleaning, and material safety, referring to the analysis of pet drinking behavior, as shown in Table 2. Furthermore, a questionnaire survey was conducted to collect key product design elements influencing pet owners' requirements, including water and electrical safety, operational safety, user-friendly prompts, intelligent monitoring, color, water purification, tissue cleaning, and long endurance. The survey involved 4 executives from pet product manufacturing companies, 6 pet product designers, and 20 pet owners, for a total of 30 respondents. Ultimately, twelve sub-criteria layers were determined and incorporated into the AHP model to develop the indicator system, as illustrated in Figure 1. Specifically, the pet water fountain model includes one target layer, four criterion layers, twelve sub-criterion layers, and three scheme layers. This model facilitates the systematic evaluation of pet water fountains, resulting in the AHP model for design evaluation. The target layer represents the optimal design scheme (A) for pet water fountains. The criteria layer encompasses functionality (B1), safety (B2), appearance (B3), and interactivity (B4). The sub-criteria layer includes drinking water promotion (C1), water purification (C2), and low noise and endurance (C3), among others.

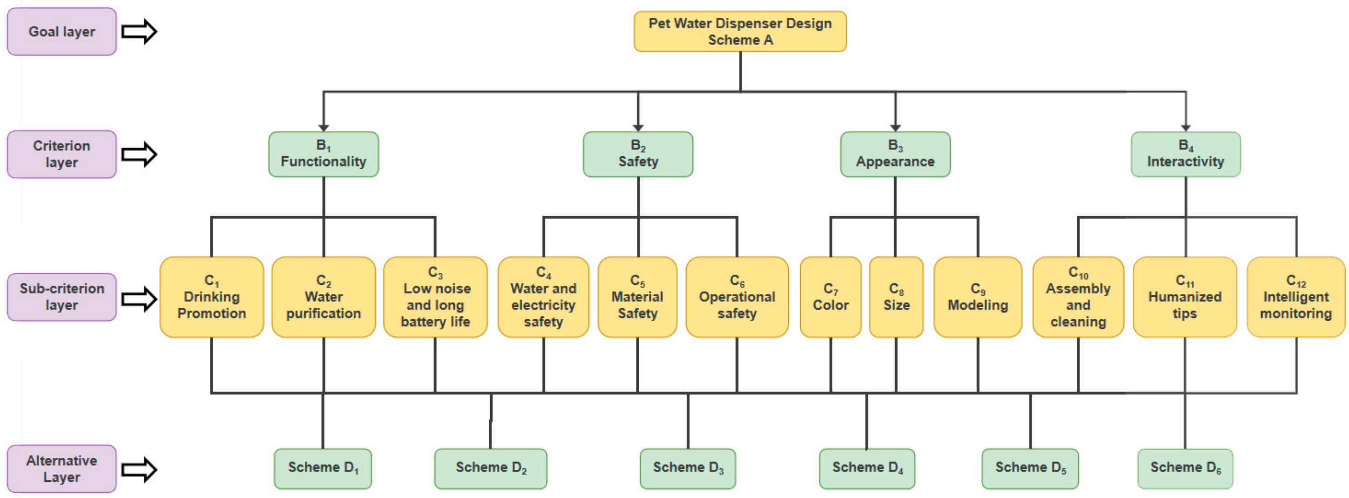


Figure 1. Analytic hierarchy process model for design evaluation of intelligent pet water fountains.

The development of a rigorous and scientific indicator system, grounded in the analysis of comparable product designs, pet drinking behaviors, and user expert surveys, ensures the system's integrity. The completeness of the constructed indicators is further validated by referencing the four criterion layers and thirteen sub-criterion layer design elements established in the pet home product design outlined in [25].

Then, 30 respondents were continuously asked to rate each indicator. The Pearson coefficient r_{xy} between any two sub-indicators was then determined using the specified formula. All coefficients were less than 0.7, indicating no redundancy among the 12 indicators.

$$r_{xy} = \frac{\sum_{k=1}^{n}(x_k - \overline{x})(y_k - \overline{y})}{\sqrt{\sum_{k=1}^{n}(x_k - \overline{x})^2} \cdot \sqrt{\sum_{k=1}^{n}(y_k - \overline{y})^2}} \quad (1)$$

in which x_k and y_k represent the ratings of the k-th respondent on indicators x and y, respectively. $\overline{x}$ and $\overline{y}$ represent the average scores of all respondents on indicators x and y, respectively. n is the effective sample size of respondents that $n \leq 30$.

4. Comprehensive Design Evaluation Using Integrated AHP-Improved CRITIC-TOPSIS Methods

4.1. Product Design Evaluation Process

Based on the previously constructed evaluation index system, the AHP method is first applied to determine the subjective weights of each index. These are then integrated with objective weights calculated using the improved CRITIC method to obtain comprehensive weights, thereby reducing the impact of subjective uncertainty and other influencing factors on the design. Subsequently, the TOPSIS method is used to rank the design schemes and select the optimal one, resulting in an integrated AHP-improved CRITIC-TOPSIS comprehensive evaluation approach. The specific evaluation process is illustrated in Figure 2.

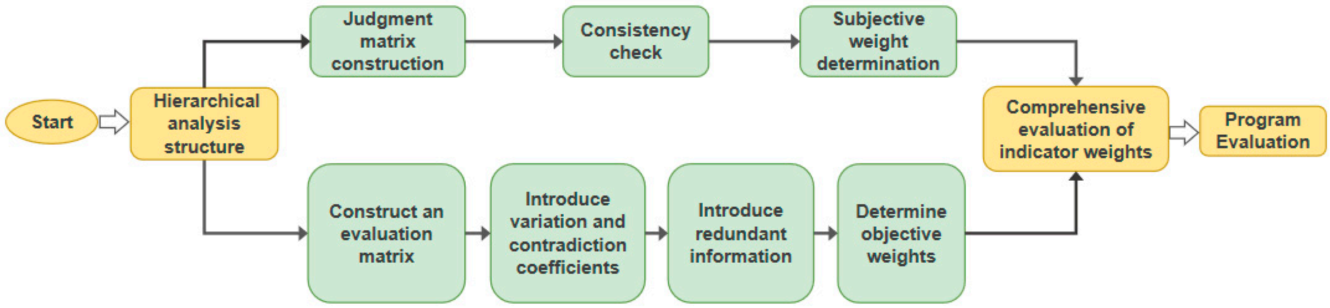


Figure 2. Evaluation process of intelligent pet water fountains.

4.2. AHP Calculation Method

The subjective weight calculation method applied in this study is based on the AHP model, which quantifies subjective influencing factors in product design and provides a systematic approach for analyzing the hierarchical structure of these factors. The AHP is employed to clarify the relationships among product design elements and to determine the weight of each element through quantitative analysis. The specific method and process are outlined below:

Step 1: A multi-level hierarchical structure model of the scientific system is constructed, incorporating subjective preference factors influencing the design of pet water fountains. A 1–9 degree multi-scale value table [26], as presented in Table 3, is used to quantitatively evaluate each indicator.

Table 3. Meaning of multi-scale value.

Scale Value	Meaning
1	Equally important
3	Somewhat important
5	Relatively important
7	Clearly important
9	Very important
2, 4, 6, 8	At the intermediate scale value

Step 2: Indicators at each level are compared pairwise to determine the relative importance of each indicator within its level. A weighted calculation is then performed, followed by the construction of a judgment matrix. Consistency testing is conducted using Equations (2) and (3) [27]. The calculation method for the consistency index (CI) is as follows.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

where λ_{max} represents the maximum eigenvalue of the matrix; n is the order of the matrix. Afterwards, the random consistency ratio (CR) was used for consistency testing, which is calculated by the following method:

$$CR = \frac{CI}{RI} \tag{3}$$

where RI represents the average random consistency index, as shown in Table 4. $CR < 0.10$ indicates qualification; otherwise, the matrix needs to be modified and rechecked.

Table 4. Consistency check indicator.

n	1	2	3	4	5	6	7
RI	0	0	0.52	0.89	1.12	1.26	1.36

Step 3: The indicators' total weights are ranked to determine the subjective weight, M_i. Indicators with higher weight values are considered more important.

4.3. Improve CRITIC Calculation Method

The AHP method provides a systematic approach to calculating the weights of each indicator, thereby facilitating evaluation and ranking. However, the subjective nature of its weighting method introduces limitations for design evaluation, potentially reducing accuracy and scientific rigor. To address this, a combination of AHP subjective weighting and the CRITIC objective weighting method is frequently employed to determine composite weights. This approach constructs a weight calculation model by quantifying both the degree of dispersion and the correlation among indicators, thereby minimizing the influence of indicator correlation on weight allocation. As a result, the final weight distribution is more scientific, objective, and aligned with the evaluation model's requirements.

The CRITIC method [28] evaluates the contrast strength between indicators using standard deviation and assesses conflicts between indicators through correlation coefficients. However, it primarily considers data variability and does not fully capture the distribution characteristics of indicator values, such as the degree of dispersion represented by information entropy. To address this limitation, information entropy redundancy is introduced to quantify indicator dispersion, resulting in a combined approach that integrates the CRITIC method with information entropy to form an improved CRITIC method [29]. Compared to the traditional CRITIC method, this enhanced approach incorporates additional indicator information provided by information entropy, alongside variability and conflict, thereby enabling weight allocation to more accurately reflect the inherent characteristics of indicators. This improvement enhances the robustness and accuracy of evaluation results. The method is particularly applicable to product designs with complex user experiences, such as pet water fountains. In this study, objective and comprehensive weights were determined using Equations (4)–(10), based on specified indicator parameters and the improved methodology, as follows.

Step 1: For m schemes containing n indicators, the judgment matrix can be expressed as

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n1} & x_{n2} & x_{n3} & x_{nm} \end{bmatrix} \tag{4}$$

where x_{ij} represents the value of the i-th indicator on the j-th scheme.

Step 2: The coefficient of variation and the coefficient of contradiction for each indicator are determined using the following method.

$$\overline{x_i} = \frac{\sum_{j=1}^{m} x_{ij}}{m} \quad (5)$$

$$H_i = \frac{\sqrt{\frac{1}{m}\sum_{j=1}^{m}\left(x_{ij} - \overline{x_i}\right)^2}}{\overline{x_i}} \quad (6)$$

where $\overline{x_i}$ represents the average weight of each evaluation indicator; H_i represents the coefficient of variation. The coefficient of contradiction for each indicator should be calculated using the following method:

$$L_i = \sum_{k=1}^{n}(1 - P_{ik}) \quad (7)$$

where P_{ij} represents the Pearson correlation coefficient between the i-th and k-th indicators; L_i represents the coefficient of contradiction.

Step 3: The information entropy redundancy of each indicator δ_i is determined using the following method

$$\delta_i = 1 + \frac{1}{\ln m}\sum_{j=1}^{m}\left[\frac{x_{ij}}{\sum_{j=1}^{m} x_{ij}}\ln\left(\frac{x_{ij}}{\sum_{j=1}^{m} x_{ij}}\right)\right] \quad (8)$$

Step 4: The following method is employed to calculate the information content of each indicator G_{i}:

$$G_{\mathrm{i}} = (H_i + \delta_i) \times L_i \quad (9)$$

Step 5: The objective weights of each indicator N_{i} are determined using the following method:

$$N_{\mathrm{i}} = \frac{G_{\mathrm{i}}}{\sum_{i=1}^{n} G_{\mathrm{i}}} \quad (10)$$

4.4. Comprehensive Weight Calculation Method

The comprehensive weight is calculated. To ensure the comprehensive weight closely aligns with both subjective and objective weights without bias, the comprehensive weight for each indicator W_i is determined using the Geometric mean method as follows:

$$W_i = \frac{\sqrt{M_i N_i}}{\sum_{i=1}^{n}\sqrt{M_i N_i}} \quad (11)$$

where M_i and N_i represent the subjective and objective weights of each indicator, respectively.

4.5. The Ideal Ranking Calculation Method Based on TOPSIS

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [30] distance ranking algorithm for multi-criteria decision-making determines the geometric distance between each candidate solution and both the theoretical optimal solution (positive ideal solution) and the worst solution (negative ideal solution) to facilitate optimal solution selection. The following section summarizes the specific methods and processes employed.

Step 1: Formula (12) is applied to further standardize the initial judgment matrix X, resulting in the standardized matrix Y.

$$y_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}} \quad (12)$$

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1m} \\ y_{21} & y_{22} & \cdots & y_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ y_{n1} & y_{n2} & y_{n3} & y_{nm} \end{bmatrix} \tag{13}$$

Step 2: Formula (13) is applied to normalize matrix Y, after which appropriate weights are assigned to obtain the weighted normalization matrix Z.

$$z_{ij} = y_{ij} \times W_i \tag{14}$$

$$Z = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1m} \\ z_{21} & z_{22} & \cdots & z_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ z_{n1} & z_{n2} & z_{n3} & z_{nm} \end{bmatrix} \tag{15}$$

Step 3: The weighted normalization matrix Z indicates that the maximum value of each indicator represents the positive ideal solution z_j^p, whereas the minimum value corresponds to the negative ideal solution z_j^n. Using the indicator parameters, the ideal solution distance for each evaluation scheme should be calculated according to Formulas (16) and (17). This process yields both the positive solution distance d_j^+ and the negative ideal solution distance d_j^-.

$$d_j^+ = \sqrt{\sum_{j=1}^{m} \left(z_j^p - z_{ij}\right)^2} \tag{16}$$

$$d_j^- = \sqrt{\sum_{j=1}^{m} \left(z_j^n - z_{ij}\right)^2} \tag{17}$$

Step 4: Formula (19) is applied to determine the relative closeness of each scheme.

$$U_j = \frac{d_j^-}{d_j^+ + d_j^-} \tag{18}$$

In which $0 \leq U_j \leq 1$. A larger U_j value indicates that the j-th scheme performs more favorably.

5. Design Scheme Evaluation and Improvement

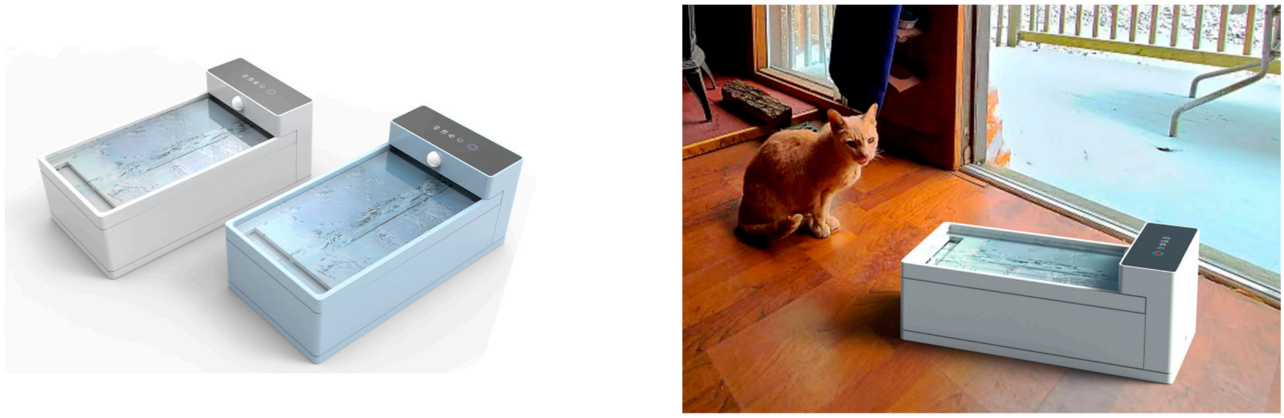
5.1. Design Scheme Explanation

Drawing upon research on comparable products, user surveys, and analysis of pet drinking behavior, and taking into account the requirements of both humans and pets, as well as design elements endorsed by experts, business owners, and pet product designers, six design schemes for pet water fountains are proposed, as illustrated in Figure 3.

All six design schemes adequately address pets' daily drinking water requirements and the practical needs of pet owners, while ensuring essential operational functions. However, each design scheme emphasizes distinct aspects, as outlined below.

Scheme D1 prioritizes safety, encompassing water and electrical safety, material safety, and operational safety. The rectangular configuration maximizes space efficiency, improves stability, and allows for adaptable indoor placement. Modular construction, along with the separation of water and electrical components, facilitates safe disassembly and maintenance.

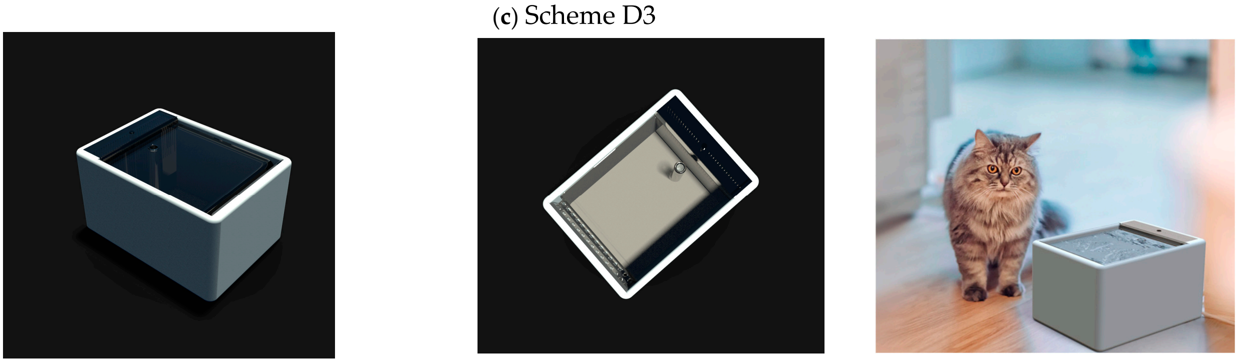
Scheme D2 prioritizes visual aesthetics by focusing on color, size, and styling using the Color, Material, and Finish (CMF) design approach. The upper section uses semi-transparent materials, which contrast with opaque materials in the lower section. Waistline lighting contributes to a layered and visually engaging texture. Additionally, a variety of color schemes enhances the product's distinctiveness and accommodates diverse user preferences.



(**a**) Scheme D1

(**b**) Scheme D2

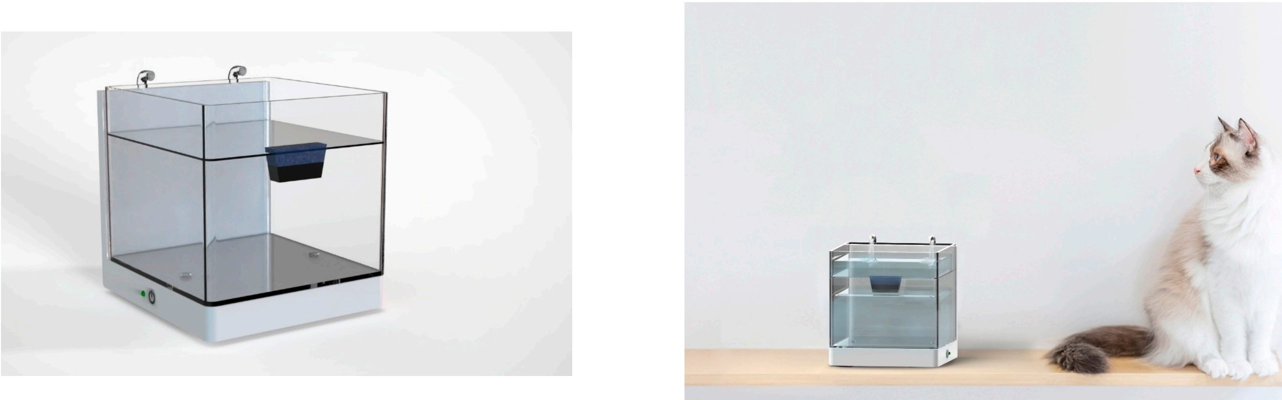
(**c**) Scheme D3



(**d**) Scheme D4

Figure 3. *Cont.*

(**e**) Scheme D5



(**f**) Scheme D6

Figure 3. Six design schemes for intelligent pet water fountains: (**a**) Scheme D1; (**b**) Scheme D2; (**c**) Scheme D3; (**d**) Scheme D4; (**e**) Scheme D5; (**f**) Scheme D6.

Scheme D3 emphasizes functional performance by incorporating features such as drinking water promotion, water purification, low noise output, and extended operational endurance. The design employs a gushing water system with four filtration layers to improve water quality and stimulate pet hydration. Additionally, a silent water pump reduces stress responses in pets, while a base-integrated battery module substantially extends operational duration.

Scheme D4 emphasizes interactivity through a straightforward and clear form. Its simple structure facilitates easy operation and cleaning. A large electronic screen and integrated lighting on the upper section enhance user interaction and information accessibility.

Scheme D5 emphasizes safety and interactivity by utilizing a stable rectangular structure that minimizes the risk of overturning and allows for adaptable indoor placement. The design isolates the charging power supply from water and electrical components and integrates modular features to improve both safety and the convenience of disassembly and cleaning. A pressure sensor located in the lower section monitors changes in water volume and facilitates intelligent tracking of cats' daily water intake, thereby meeting users' needs for remote monitoring.

Scheme D6 integrates functionality and appearance through the inclusion of a tailless power supply and a water–electricity separation design. Its modular structure enhances safety and allows for efficient disassembly and cleaning. The product adopts a simple geometric form that is both concise and dynamic, with two prominent water inlets functioning as decorative focal points. The flowing arc of the water unites dynamic and static elements within the design. Additionally, the combination of a large transparent water tank and a white body establishes a pronounced material contrast, creating a sense of transformation between virtual and real elements that elevates the product's ornamental value.

5.2. Design Scheme Evaluation

5.2.1. Subjective Weight Calculation

Based on the previously established hierarchical analysis model for pet water fountains, 30 respondents (four executives, six designers, and twenty pet owners) were invited to use the 1–9 scale method described in Table 2 to quantitatively score each indicator. Judgment matrices for each hierarchical element were generated through pairwise comparison. The subjective weights of each indicator were calculated, as presented in Tables 5–9. The data in these tables, excluding the weights, represent the relative importance of each indicator in pairwise comparisons. The aggregation process for the 30 respondents utilizes the Aggregation of Individual Judgments (AIJ) method. The priority derivation method can be described as first synthesizing the judgment matrices of all respondents to form a "group judgment matrix", and then calculating the final weights based on this synthesis matrix. The comprehensive score for each unit within the matrix R_{ij} is calculated as the geometric mean of all respondents' values using the following method:

$$R_{ij} = \sqrt[m]{\prod_{k=1}^{k=m} R_{ij}^{k}} \quad (19)$$

where R_{ij}^{k} is the rating of the k-th respondent, and m is the number of respondents.

Table 5. Criteria layer judgment matrix and weights.

A	B_1	B_2	B_3	B_4	Weight
B_1	1	7/6	1/6	1/2	0.3529
B_2	6/7	1	1/7	3/7	0.4118
B_3	6/1	7	1	3	0.0588
B_4	2	7/3	1/3	1	0.1765

Table 6. Function criteria layer judgment matrix and weights.

B_1	C_1	C_2	C_3	Weight
C_1	1	7/6	5/6	0.3333
C_2	6/7	1	5/7	0.3889
C_3	6/5	7/5	1	0.2778

Table 7. Security criteria judgment matrix and weights.

B_2	C_4	C_5	C_6	Weight
C_4	1	8/9	2/3	0.3913
C_5	9/8	1	3/4	0.3478
C_6	3/2	4/3	1	0.2609

Table 8. Aesthetic criteria judgment matrix and weights.

B_3	C_7	C_8	C_9	Weight
C_7	1	2	3/2	0.2222
C_8	1/2	4/3	3/4	0.4445
C_9	2/3	1/4	1	0.3333

Table 9. Interaction criterion judgment matrix and weights.

B_4	C_{10}	C_{11}	C_{12}	Weight
C_{10}	1	4/5	1/5	0.5
C_{11}	5/4	1	1/4	0.4
C_{12}	5	4	1	0.1

When applying the aggregated individual priority (AIP) method to AHP data from 30 respondents, there is no single aggregated judgment matrix, so the CI/CR of an aggregated matrix cannot be directly reported. Instead, overall data reliability can be assessed using statistical individual consistency indicators, and a local-to-global weight validation table can be created to illustrate the transfer of final weights. Table 10 presents the consistency calculation results for target layer A and criterion layer B. The CR values for each element are below 0.1, which demonstrates that the judgment matrix and its results have passed the consistency test and are considered feasible.

Table 10. Consistency result verification.

	A	B_1	B_2	B_3	B_4
λ_{max}	4.132	3.0142	3.0324	3.0385	3.0536
CI	0.044	0.0071	0.0162	0.0193	0.0268
RI	0.89	0.52	0.52	0.52	0.52
CR	0.049438	0.013654	0.031154	0.037115	0.051538

The global weight vector of the sub-criterion layer relative to the target system is obtained by weighting and integrating the weight coefficients of each criterion layer. Following these calculations, an overall ranking is conducted to determine the subjective weight ranking of each element in the sub-criterion layer. The results are presented in Table 11. The weights of the 12 indicators presented in Columns 2 to 5, as derived from Tables 6–9, represent their local weights relative to their respective parent levels. In contrast, the subjective weights M_i, calculated in Column 6, indicate their global weights within the overall product design indicator system.

Table 11. Subjective total weight obtained from the AHP model.

Evaluation Indicators	B_1 Functionality (0.3529)	B_2 Safety (0.4118)	B_3 Appearance (0.0588)	B_4 Interactivity (0.1765)	Subjective Weight M_i	Ranking
C_1: Drinking water promotion	0.3333				0.1176	4
C_2: Water purification	0.3889				0.1372	3
C_3: Low noise and long battery life	0.2778				0.098	6
C_4: Water and electricity safety		0.3913			0.1611	1
C_5: Material safety		0.3478			0.1432	2
C_6: Operational safety		0.2609			0.1074	5
C_7: Color			0.2222		0.0131	12
C_8: Size			0.4444		0.0261	9
C_9: Modeling			0.3333		0.0196	10
C_{10}: Assembly and cleaning				0.5	0.0883	7
C_{11}: Humanized tips				0.4	0.0706	8
C_{12}: Intelligent monitoring				0.1	0.0177	11

5.2.2. Objective Weight Calculation

We presented six design schemes (D1–D6) to 30 respondents, each accompanied by detailed internal structure and functional diagrams, along with dimension annotations.

They were asked to rate each scheme on 12 indicators, using the following scale: 0–30 for rejection, 31–50 for relative acceptance, 51–60 for good, 61–80 for excellent, and 81–100 for outstanding. The average score for each scheme was calculated, and Equation (3) was used to create the initial judgment matrix, as shown in Table 12. The objective weight values of the indicators were determined using Equations (4) through (9), as presented in Table 13.

Table 12. Initial judgment matrix X.

Evaluation Indicators	Scheme D1	Scheme D2	Scheme D3	Scheme D4	Scheme D5	Scheme D6
C_1: Drinking water promotion	72	65	75	68	69	76
C_2: Water purification	64	66	74	65	70	73
C_3: Low noise and long battery life	67	63	73	66	65	75
C_4: Water and electricity safety	82	68	71	70	80	70
C_5: Material safety	78	73	66	69	79	71
C_6: Operational safety	77	65	72	68	76	69
C_7: Color	61	72	64	62	63	71
C_8: Size	69	75	68	69	68	74
C_9: Modeling	66	73	67	67	66	72
C_{10}: Assembly and cleaning	73	70	70	78	77	71
C_{11}: Humanized tips	68	64	65	72	74	66
C_{12}: Intelligent monitoring	65	61	62	69	70	63

Table 13. Objective weight of each indicator.

Evaluation Indicators	Information Amount G_i	Objective Weight N_i
C_1: Drinking water promotion	0.5766	0.115
C_2: Water purification	0.4339	0.0839
C_3: Low noise and long battery life	0.4790	0.0926
C_4: Water and electricity safety	0.5848	0.1131
C_5: Material safety	0.5061	0.0979
C_6: Operational safety	0.4718	0.0912
C_7: Color	0.3200	0.0619
C_8: Size	0.3244	0.0627
C_9: Modeling	0.3285	0.0635
C_{10}: Assembly and cleaning	0.3620	0.0700
C_{11}: Humanized tips	0.4074	0.0788
C_{12}: Intelligent monitoring	0.3765	0.0728

5.2.3. Comprehensive Weight Calculation

Variations in observation perspectives, calculation methods, and scoring strategies commonly result in discrepancies between subjective and objective weight calculation outcomes. In the design evaluation of pet water fountains presented in this article, subjective weights primarily reflect user needs, whereas objective weights emphasize the product environment and pet requirements. Consequently, such differences are expected. Thus, the introduction of comprehensive weight calculation is required to achieve a balance between subjective and objective indicators.

The subjective and objective comprehensive weights were calculated using Equation (11), as presented in Table 14. The overall ranking of the importance of each element is illustrated in Figure 4. In terms of criteria, safety is prioritized over functionality, interactivity, and aesthetic requirements. This suggests that, during product design and system optimization, functionality should remain a primary consideration. Regarding specific elements, water and electricity safety, drinking water promotion, material safety, water purification, operational safety, low noise and endurance, assembly and cleaning, size, shape, humanized prompts, intelligent monitoring, and color are ranked in descending order of importance.

The weight calculation results indicate that the top five factors influencing the functional design of pet water fountains are water and electricity safety (0.290), drinking water promotion (0.139), material safety (0.128), water quality purification (0.109), and operational safety (0.063). This quantitative analysis demonstrates that these indicators are critical to product efficiency, underscoring their theoretical significance as key evaluation criteria.

Table 14. Comprehensive weight of each indicator.

Evaluation Indicators	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
Comprehensive weight	0.1143	0.0973	0.0767	0.1320	0.1015	0.0710	0.0410	0.0831	0.0631	0.1044	0.0940	0.0217

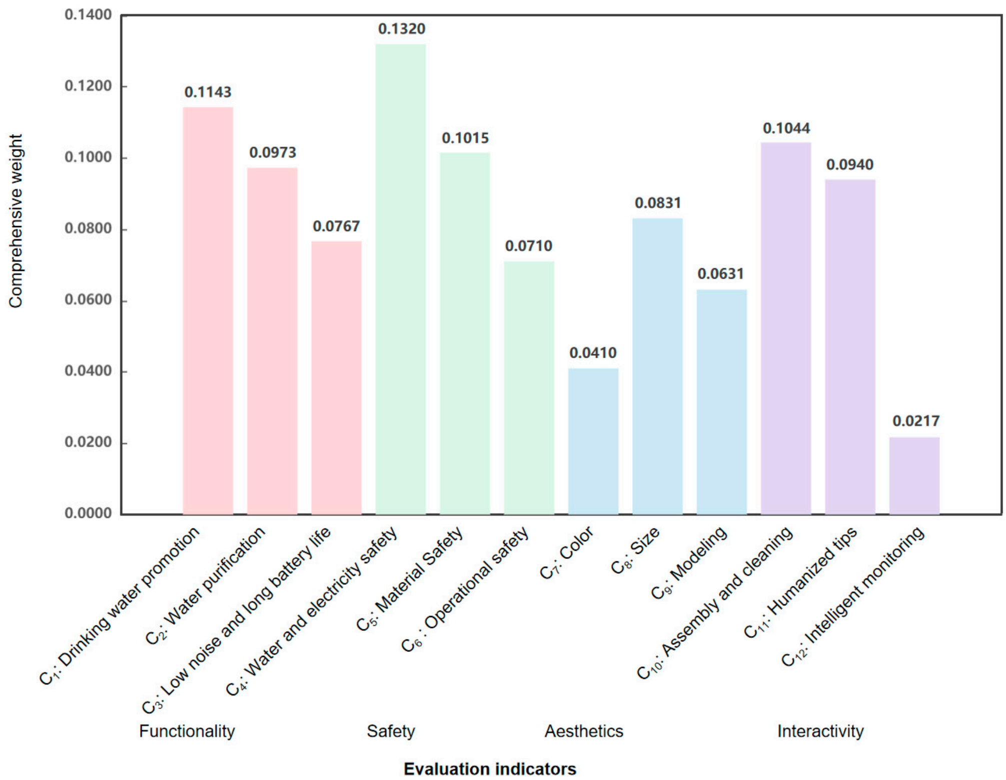


Figure 4. Comprehensive weight values of each evaluation indicator.

5.2.4. Design Scheme Ranking

The previously proposed comprehensive design evaluation system, based on a multi-criteria decision-making method, is applied to calculate and rank the weights of the various impact indicators for the three schemes. This process facilitates the selection of the optimal design scheme.

Based on the initial judgment matrix X in Table 12, the standardized matrix Y is computed using Equation (12), and the results are shown in Table 15.

Based on the standardization matrix Y in Table 15 and the comprehensive weights of each indicator in Table 14, the weighted normalization matrix Z is derived using Equations (14) and (15), as presented in Table 16. The calculation code implemented with Python 6.3 tools is provided in Appendix A.1.

Finally, using the weighted normalization matrix Z presented in Table 16, the positive and negative ideal solution distances and the relative closeness for the six schemes are calculated according to Equations (16)–(18). The results are shown in Table 17. The calculation code implemented with Python tools is provided in Appendix A.2.

Table 15. Standardization matrix Y.

Evaluation Indicators	Scheme D1	Scheme D2	Scheme D3	Scheme D4	Scheme D5	Scheme D6
C_1: Drinking water promotion	0.4081	0.3685	0.4422	0.3855	0.3912	0.4479
C_2: Water purification	0.3799	0.3918	0.4393	0.3859	0.4155	0.4334
C_3: Low noise and long battery life	0.4005	0.3766	0.4363	0.3945	0.3885	0.4483
C_4: Water and electricity safety	0.4543	0.3767	0.3933	0.3878	0.4432	0.3878
C_5: Material safety	0.4374	0.4094	0.3701	0.3869	0.4431	0.3981
C_6: Operational safety	0.4410	0.3722	0.4124	0.3894	0.4352	0.3952
C_7: Color	0.3857	0.4363	0.4047	0.3921	0.3984	0.4300
C_8: Size	0.3992	0.4340	0.3934	0.3992	0.3934	0.4282
C_9: Modeling	0.3930	0.4347	0.3990	0.3990	0.3930	0.4288
C_{10}: Assembly and cleaning	0.3987	0.3928	0.3869	0.4463	0.4345	0.3869
C_{11}: Humanized tips	0.4017	0.3895	0.3835	0.4382	0.4322	0.4017
C_{12}: Intelligent monitoring	0.4132	0.3878	0.3941	0.4068	0.4449	0.4005

Table 16. Weighted normalization matrix Z.

Evaluation Indicators	Scheme D1	Scheme D2	Scheme D3	Scheme D4	Scheme D5	Scheme D6
C_1: Drinking water promotion	0.0466	0.0421	0.0505	0.0441	0.0447	0.0512
C_2: Water purification	0.0370	0.0381	0.0427	0.0375	0.0404	0.0422
C_3: Low noise and long battery life	0.0307	0.0289	0.0335	0.0303	0.0298	0.0344
C_4: Water and electricity safety	0.0600	0.0497	0.0519	0.0512	0.0585	0.0512
C_5: Material safety	0.0444	0.0416	0.0376	0.0393	0.0450	0.0404
C_6: Operational safety	0.0313	0.0264	0.0293	0.0276	0.0309	0.0281
C_7: Color	0.0158	0.0179	0.0166	0.0161	0.0163	0.0176
C_8: Size	0.0332	0.0361	0.0327	0.0332	0.0327	0.0356
C_9: Modeling	0.0248	0.0274	0.0252	0.0252	0.0248	0.0271
C_{10}: Assembly and cleaning	0.0416	0.0410	0.0404	0.0466	0.0454	0.0404
C_{11}: Humanized tips	0.0378	0.0366	0.0360	0.0412	0.0406	0.0378
C_{12}: Intelligent monitoring	0.0090	0.0084	0.0086	0.0088	0.0097	0.0087

Table 17. Relative closeness of each scheme.

	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6
d_j^+	0.01115	0.01817	0.01451	0.01534	0.00969	0.01267
d_j^-	0.01432	0.00638	0.01176	0.00888	0.01482	0.01317
U_j	0.5622	0.2598	0.4477	0.3668	0.6048	0.5097
Ranking order	2	6	4	5	1	3

When we institute the Ranking method from the TOPSIS method into VIKOR or PROMETHEE, the ranking results have undergone some changes. The ranking results using the VIKOR method are D6 > D4 > D5 > D1 > D3 > D2, while the ranking results using the PROMETHEE method are D6 > D5 > D1 > D3 > D2 > D4.

Three distinct ranking methods have demonstrated varying levels of effectiveness across multiple application domains. Expert evidence indicates that the TOPSIS ranking method is particularly suitable for evaluating pet water fountain designs. The evaluation process for these designs typically involves multiple indicators and considers various alternative solutions. The TOPSIS method effectively integrates both benefit-oriented indicators, such as filtering effectiveness, and cost-oriented indicators, such as noise levels. By normalizing vectors, TOPSIS facilitates the comparison of these indicators within a unified framework, preventing dominance by indicators with larger numerical values due to differing units. Moreover, the TOPSIS method utilizes raw data from multiple alternatives and reduces the influence of subjective weighting. Comparative experiments presented in the following sections will confirm the accuracy of the proposed method.

5.3. Evaluation Results and Design Scheme Improvement

A higher degree of closeness indicates a superior solution. Accordingly, the ranking of solutions is as follows: D5 (focus on security + interactivity) > D1 (focus on security) > D6 (focus on functionality + appearance) > D3 (focus on functionality) > D4 (focus on interactivity) > D2 (focus on appearance). Therefore, considering cost control, Scheme 5, which prioritizes enhanced safety and interactivity design, represents the optimal solution. Following prototype development and physical testing, the scheme was implemented in practice, and both functional testing and user evaluations yielded positive results.

Multi-index weight analysis and scheme priority evaluation demonstrate that safety factors in the design of pet water fountains are prioritized above functional, interactive, and aesthetic factors. Within the indicator system hierarchy, the top five elements are water and electricity safety, drinking water promotion, assembly and cleaning, material safety, and water purification. While optimizing performance indicators generally leads to superior solutions, it is also essential to consider cost control. Further research is required to develop strategies that balance development costs and product performance, thereby enabling the selection of optimal solutions within the expected cost range. In practice, integrating key user requirements while minimizing costs and enhancing efficiency enables optimal product design under limited conditions. Consequently, product improvement should prioritize safety (including water and electricity safety, material safety, and operational safety) and functionality (such as drinking water promotion, water purification, low noise, and long endurance). Enhancements to assembly and cleaning processes, combined with the integration of intelligent technologies such as health and environmental monitoring, and user-friendly prompts, including lighting and voice cues, address pet owners' requirements for improved hygiene and convenience. Additionally, these features facilitate owners' understanding of their pets' physiological states, support disease prevention, and strengthen emotional bonds through scientific feedback.

5.4. Effectiveness Verification for the Proposed Method

5.4.1. Comparative Experiment Verification

To assess the effectiveness of the proposed approach, a comparison was conducted among the AHP-unimproved CRITIC-TOPSIS method, the AHP fuzzy comprehensive evaluation method [31], and the proposed method.

Experimental setup: The pet water fountain indicator system described in this study was utilized. The subjective weight matrix for 12 product design indicators, derived from group ratings by 30 respondents (see Table 11), and the initial matrix of respondents' ratings for six design schemes (see Table 12), were employed to evaluate the design schemes using AHP-Fuzzy Comprehensive Evaluation method, AHP-unimproved CRITIC-TOPSIS, and the proposed method. The comparative results are presented in Table 18. The evaluation process for the three options is outlined below.

1. Design scheme evaluation process with the AHP-Fuzzy comprehensive evaluation method: The initial judgment matrix X, reflecting expert and user ratings for each indicator scheme as presented in Table 12, was combined with the subjective weights M_i for each indicator from Table 11. The fuzzy comprehensive evaluation method was then applied to calculate the scores for each scheme. The results are presented in Table 18.
2. Design scheme evaluation process with the AHP-unimproved CRITIC-TOPSIS method: The objective weight $N_{\mathrm{i}}^{\mathrm{u}}$ for each indicator is calculated from the initial judgment matrix X in Table 12 using the traditional CRITIC method. This value is then combined with the subjective weight M_i from Table 11 to determine the comprehensive weight C_i^u for each indicator. The initial judgment matrix X is subsequently converted into a standard weighting matrix Z^u using these comprehensive weights.

The TOPSIS method is then applied to calculate the scores for each scheme based on the standard weighting matrix Z^u. The results are presented in Table 18.

3. Design scheme evaluation process with the proposed method: Based on the standard weighting matrix Z presented in Table 12, the TOPSIS method was applied to calculate the scores for each scheme. The results are provided in Table 18.

Table 18. Comparison of different methods.

Methods	Scheme D1	Scheme D2	Scheme D3	Scheme D4	Scheme D5	Scheme D6
AHP-Fuzzy comprehensive evaluation	0.5811	0.1634	0.4384	0.3214	0.6891	0.5332
AHP-unimproved CRITIC-TOPSIS	0.6730	0.2245	0.4227	0.2466	0.6977	0.4530
Proposed method	0.5622	0.2598	0.4477	0.3668	0.6048	0.5097
Ranking order	2	6	4	5	1	3

The evaluation results from the three methods are consistent, each yielding the ranking D5 > D1 > D6 > D3 > D4 > D2. This consistency supports the reliability of the proposed method.

5.4.2. Sensitivity Analysis Report

The method proposed in this article was applied for the sensitivity analysis of product design evaluation. To assess the impact of weight uncertainty on ranking, Monte Carlo simulations were conducted on the weights of each method as follows.

Disturbance setting: The weight of each indicator was assumed to fluctuate by ±10% from its original value, following a uniform distribution that $\mathrm{w_i} \sim \left(0.9\mathrm{w_i^0}, 1.1\mathrm{w_i^0}\right)$. The generated weight vector was then normalized so that its sum equaled 1.

Simulation frequency: Each method independently generated 1000 sets of random weights.

Evaluation indicators: For each weight group, the closeness of each scheme was calculated. The frequency of each ranking, as well as the mean and standard deviation of closeness for each scheme, were also determined. The results are presented in Table 19.

Table 19. Sensitivity analysis report of the proposed method.

Schemes	Mean Closeness	Standard Deviation	95% Confidence Interval	Ranking First Frequency	Ranking Last Frequency
Scheme D1	0.5938	0.012	[0.570, 0.617]	0%	0%
Scheme D2	0.2759	0.010	[0.256, 0.296]	0%	100%
Scheme D3	0.4311	0.011	[0.409, 0.453]	0%	0%
Scheme D4	0.3382	0.009	[0.321, 0.356]	0%	0%
Scheme D5	0.6335	0.010	[0.614, 0.653]	100%	0%
Scheme D6	0.4974	0.011	[0.476, 0.519]	0%	0%

The simulation experiment process and sensitivity analysis report provided additional verification of the method's accuracy and reliability. The detailed analysis is presented below.

Stability: In the simulation experiment, when the weight fluctuated within ±10%, the rankings of the optimal solution D5 and the worst solution D2 remained unchanged. The relative order of the other solutions was generally stable, with only minor local variations. The intermediate rankings (D1, D6, D3, D4) occasionally shifted under disturbance; however, the probability that D1 consistently outperformed D6 was 97%, and the probability that D6 outperformed D3 was 95%. Overall, the ranking reliability of this method exceeded that of the other two methods.

Uncertainty range: The sensitivity analysis demonstrated that the standard deviation of closeness for each scheme is approximately 0.01, while the width of the 95% confidence interval remains below 0.05. These results indicate that the evaluation outcomes possess high accuracy and credibility.

5.4.3. Discuss

Comparative experiments and sensitivity analyses demonstrate that the AHP-improved CRITIC-TOPSIS method proposed in this study reliably and accurately evaluates pet water fountain design schemes. By assigning weights to each influencing indicator and ranking their impacts, this approach enhances the objectivity of data evaluation and the precision of ranking outcomes. The experimental process and results validate the effectiveness of the proposed method for the construction and design evaluation of pet water fountains. Additionally, this research addresses a gap in comparative studies by examining the proposed method alongside alternative approaches in the field of pet product design.

Traditional multi-criteria decision-making (MCDM) methods often exhibit limitations such as weak semantic expression, single-weight modeling, and insufficient ranking robustness in product design evaluation [32]. This article applies the comprehensive weighting method to increase the accuracy of product design element feature representation and integrates the ideal ranking method to strengthen the robustness of scheme evaluation and ranking. In comparison to the AHP-Fuzzy comprehensive evaluation method, the comprehensive weighting method proposed in this study more accurately reflects the relative importance of each design element. While the fuzzy comprehensive evaluation value indicates the degree of subjective adaptability of the scheme, this approach is highly dependent on subjective weighting. The model incorporates individual preference data from both experts and users, and considers multiple parameters, including the rights of service target groups and pet behavior characteristics, to establish a comprehensive evaluation system. These enhancements substantially increase the accuracy and objectivity of the evaluation results, thereby strengthening the scientific rigor of the research conclusions.

6. Conclusions

To address the homogenization of pet water fountains and accommodate the complex needs of users, this study developed a product design evaluation system that integrates multiple methodologies within the framework of multi-criteria decision theory. Initially, through analysis of comparable products, investigation of pet drinking behavior, and user surveys, a multi-level system of subjective evaluation indicators was established using the AHP model. The improved CRITIC method was then employed to determine both subjective and objective comprehensive weights for each indicator. Subsequently, the TOPSIS method was employed to rank six design schemes and determine the optimal solution. The product design scheme was further refined based on key indicators with higher comprehensive weights. The results of the simulation verification experiment and sensitivity analysis indicate that the proposed scheme achieves high accuracy and reliability in evaluating pet water fountain designs. The theoretical significance of this study is demonstrated by the integration of multiple multi-criteria decision-making methods within a systematic framework, as well as the introduction of a comprehensive evaluation approach that incorporates both subjective and objective factors into pet product design. Enhancements to traditional methodologies have increased the applicability of multi-criteria decision-making theory. The practical significance of the proposed system is reflected in its capacity to identify key indicators that improve the accuracy of product functions and services, thereby offering a scientific and precise evaluation system and optimization strategy for the design of pet water dispensers. Furthermore, the research findings serve as a reference for the design and development of other pet products.

However, current research primarily relies on initial user surveys and expert judgments, without extensively incorporating dynamic data generated during the long-term operation of products in real-world scenarios. Additionally, the analysis of differences in user habits and the interaction of environmental variables remains insufficient. These limitations reduce the explanatory power and predictive accuracy of models when applied to complex real-world situations. Subsequent research should incorporate a broader spectrum of functional testing and user evaluation data and establish a more comprehensive dynamic indicator evaluation system. This system should encompass dimensions such as human–computer interaction experience, long-term usage cost, and adaptability across diverse environments. Such enhancements will improve the accuracy and robustness of the evaluation model when addressing multidimensional and complex factors, thereby offering more specific and comprehensive solutions for pet product design.

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Institutional Review Board Statement: The study protocol was approved in advance by Ethics Review Committee of School of Design, Anhui Polytechnic University(No. AHPU-SOD-2025-001), 5 January 2025.

Informed Consent Statement: All participants provided informed consent to participate in the study.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Hai-Tu Miao was employed by the company Shanghai Hello Puhui Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Appendix A.1. The Python Calculation Code for Table 16

```
import numpy as np
# Table 15: Standardization Matrix (12 rows × 6 columns)
y_matrix = np.array([
[0.4081, 0.3685, 0.4422, 0.3855, 0.3912, 0.4479],
[0.3799, 0.3918, 0.4393, 0.3859, 0.4155, 0.4334],
[0.4005, 0.3766, 0.4363, 0.3945, 0.3885, 0.4483],
[0.4543, 0.3767, 0.3933, 0.3878, 0.4432, 0.3878],
[0.4374, 0.4094, 0.3701, 0.3869, 0.4431, 0.3981],
[0.4410, 0.3722, 0.4124, 0.3894, 0.4352, 0.3952],
[0.3857, 0.4363, 0.4047, 0.3921, 0.3984, 0.4300],
[0.3992, 0.4340, 0.3934, 0.3992, 0.3934, 0.4282],
[0.3930, 0.4347, 0.3990, 0.3990, 0.3930, 0.4288],
[0.3987, 0.3928, 0.3869, 0.4463, 0.4345, 0.3869],
```

```
[0.4017, 0.3895, 0.3835, 0.4382, 0.4322, 0.4017],
[0.4132, 0.3878, 0.3941, 0.4068, 0.4449, 0.4005]
])
# Table 14: Weight (12)
weights = np.array([
0.1143, 0.0973, 0.0767, 0.1320, 0.1015, 0.0710,
0.0410, 0.0831, 0.0631, 0.1044, 0.0940, 0.0217
])
# Calculate weighted normalization matrix: multiply row by row by corresponding weight
weighted_matrix = y_matrix * weights[:, np.newaxis] # Utilize broadcasting mechanism
# Output result (rounded to four decimal places)
print("Weighted Normalization Matrix(rounded to four decimal places):")
for i, row in enumerate(weighted_matrix):
print(f"C{i + 1:2d}: " + " ".join([f"{v:.4f}" for v in row]))
```

Appendix A.2. The Python Calculation Code for Table 17

```
import numpy as np
# Weighted Normalization Matrix (12 rows × 6 columns)
weighted_matrix = np.array([
[0.0466, 0.0421, 0.0505, 0.0441, 0.0447, 0.0512],
[0.0370, 0.0381, 0.0427, 0.0375, 0.0404, 0.0422],
[0.0307, 0.0289, 0.0335, 0.0303, 0.0298, 0.0344],
[0.0600, 0.0497, 0.0519, 0.0512, 0.0585, 0.0512],
[0.0444, 0.0416, 0.0376, 0.0393, 0.0450, 0.0404],
[0.0313, 0.0264, 0.0293, 0.0276, 0.0309, 0.0281],
[0.0158, 0.0179, 0.0166, 0.0161, 0.0163, 0.0176],
[0.0332, 0.0361, 0.0327, 0.0332, 0.0327, 0.0356],
[0.0248, 0.0274, 0.0252, 0.0252, 0.0248, 0.0271],
[0.0416, 0.0410, 0.0404, 0.0466, 0.0454, 0.0404],
[0.0378, 0.0366, 0.0360, 0.0412, 0.0406, 0.0378],
[0.0090, 0.0084, 0.0086, 0.0088, 0.0097, 0.0087]
])
# Positive ideal solution: the maximum value of each row
A_plus = weighted_matrix.max(axis = 1)
# Negative ideal solution: the minimum value of each row
A_minus = weighted_matrix.min(axis = 1)
# Calculate the distance between each plan
D_plus = np.sqrt(((weighted_matrix.T − A_plus) ** 2).sum(axis = 1))
D_minus = np.sqrt(((weighted_matrix.T − A_minus) ** 2).sum(axis = 1))
# Relative closeness
C = D_minus / (D_plus + D_minus)
# Output result
print("Ideal solution A+:", np.round(A_plus, 4))
print("Negative ideal solution A−:", np.round(A_minus, 4))
print("\n Distance and closeness of each scheme:")
for i in range(6):
print(f"Scheme D{i + 1}: D+ = {D_plus[i]:.5f}, D- = {D_minus[i]:.5f}, C = {C[i]:.4f}")
# Ranking
ranking = np.argsort(-C) # descending order
print("\n Sort (from best to worst):", [f"D{i + 1}" for i in ranking])
```

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