

Research on Design Decision-Making and Optimization Strategies for Elderly Companion Robots Based on a Fuzzy DEMATEL-VIKOR Hybrid Model

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Abstract—With the acceleration of global aging, companion robots for the elderly have become an important solution for alleviating loneliness and ensuring safety. However, due to the vagueness of user needs, designers often struggle to strike a balance between "functional reliability" and "emotional interaction." This study proposes a hybrid multi-criteria decision-making (MCDM) framework combining fuzzy set theory, DEMATEL, and VIKOR to optimize design strategies. First, Fuzzy DEMATEL is employed to analyze the causal relationships among evaluation criteria. The results show that "safety and reliability" are the core driving factors, while "emotional intelligence" is the most significant outcome factor, confirming that physical safety is the prerequisite for establishing emotional trust. Subsequently, the VIKOR method is used to rank four design schemes, determining that the "hybrid balanced" scheme is the best compromise solution (), significantly superior to designs oriented toward a single function. Based on this, the study proposes the "trust pyramid" model, advocating a design strategy that combines an "invisible safety net" with "proactive multi-modal empathy." This research provides a theoretical basis for the "trust-first" design paradigm in eldercare technology.

Keywords—Elderly Companion Robot, Fuzzy DEMATEL, VIKOR, MCDM, Emotional Design

I. INTRODUCTION

A. Research Background: The Rise of Companion Robots in Aged Care

Population aging has evolved from a purely demographic issue into a serious global social challenge. According to the latest statistics from the United Nations (UN) and national offices on aging, the proportion of people aged 65 and above worldwide is rising at an unprecedented rate and is expected to continue increasing in the coming decades. As a result, the number of "empty-nest elderly" is expanding, and they are facing severe social isolation, feelings of loneliness, and safety risks in the event of sudden health incidents. At the same time, the traditional function of family care-giving is gradually weakening, and there is a significant shortage of professional care-giving personnel. Against this backdrop, introducing assistive technology into elderly care — especially the development of social assistive robots (SARs) capable of providing emotional support and daily living assistance—has become an inevitable trend to alleviate care-

giving pressures and improve the quality of life for the elderly [1].

At present, a variety of companion robots have emerged on the market, such as the therapeutic seal robot Paro for emotional comfort, the humanoid robot Pepper with multi-modal interaction capabilities, and pet-like home robots like the Sony Aibo. Although these products have alleviated loneliness among the elderly to some extent, designers often face a "decision dilemma" when it comes to practical application and promotion. Existing products frequently display an imbalance between "function stacking" and "deep emotional interaction," or encounter conflicts between pursuing "high-tech intelligence" and ensuring the "ease of use" required by elderly users. Designers often find it difficult to accurately determine which core needs should be prioritized under limited resources.

The fundamental cause of the aforementioned predicament lies in the limitations of current design decision-making methods. Present research on the design of companion robots largely relies on the designers' subjective intuition or simple quantitative analysis methods such as user questionnaires. These traditional approaches tend to consider each design metric in isolation, lacking consideration for the inherent "ambiguity" and complex "inter-dependencies" among design elements. For example, does simply improving the accuracy of speech recognition (a technical metric) directly lead to an increase in user trust (an emotional metric)? Such nonlinear causal chains are difficult to effectively quantify and analyze using conventional linear models. Therefore, there is an urgent need for a hybrid decision-making model that can handle fuzzy information and analyze the associations among complex factors in order to guide the optimal design of robots.

B. Research Objectives and Contributions

Therefore, To address the decision-making challenges arising from the subjectivity of user needs and the conflict of design objectives, this study introduces a multi-criteria decision-making (MCDM) framework based on fuzzy set theory—the Fuzzy DEMATEL-VIKOR hybrid model. The purpose of adopting this method is to solve the pain point in traditional design processes, where qualitative indicators are difficult to quantify. Specifically, Fuzzy DEMATEL is employed to accurately analyze the complex inter-

dependencies and causal relationships among design elements in a fuzzy linguistic environment; meanwhile, the VIKOR method focuses on scientifically calculating compromise solutions that are closest to the ideal, navigating among conflicting evaluation criteria such as "high-performance interaction" and "low-cost control." [2]

Based on this methodological framework, the specific objectives of this study primarily encompass the following three dimensions: (1) to establish a systematic evaluation index system for elderly companion robots, covering key aspects such as functional implementation, emotional interaction, physical safety, and ethical privacy; (2) to identify and distinguish the core driving factors and passive factors that influence elderly users' willingness to adopt, clarifying the mechanisms of action for design elements; and (3) to conduct a comprehensive assessment and ranking of different conceptual design solutions, selecting the optimal improvement path in terms of overall effectiveness.

The final contribution of this study lies not only in completing the conceptual design of a single product, but more importantly in proposing a set of reusable "evidence-based design strategies." Through quantitative analysis and model simulation, it provides scientific decision-making support for the development of future companion robots for the elderly, shifting from "intuition-driven" to "data-driven" approaches. This effectively enhances product suitability for the elderly and improves market conversion rates.

II. RELATED WORK

A. The Hybrid Decision-Making Framework

The design decision-making for companion robots for the elderly is a typical multi-criteria decision-making (MCDM) problem. Its core challenge lies in the complex interdependencies among evaluation indicators, and the fact that users' (elderly individuals and their families) needs are often highly subjective and ambiguous. To address the limitations of traditional single evaluation methods, this study constructs an integrated hybrid decision-making framework incorporating Fuzzy Set Theory, DEMATEL, and VIKOR. This framework aims to quantify the causal relationships among design elements and to identify the optimal compromise solutions from among the conflicting design criteria[3].

The hybrid model logical architecture proposed in this study is shown in Figure 1 and specifically includes the following three core stages:

First Stage: Transformation and Processing of Fuzzy Information

Due to the subjectivity of human thinking, experts or users often use linguistic variables such as "very important" or "average" rather than precise numerical values when assessing abstract indicators like "safety" and "emotional interaction." To address this uncertainty, this study introduces triangular fuzzy numbers (TFNs) to convert these qualitative linguistic evaluations into quantitative fuzzy numbers. This step effectively overcomes issues of information loss and semantic ambiguity in traditional scoring, providing a reliable data foundation for subsequent mathematical operations.

Second Stage: Identification of Key Factors and Weight Calculation Based on DEMATEL

Traditional methods (such as AHP) usually assume that evaluation criteria are independent of each other. However, in the design of companion robots, functional indicators are often interrelated (for example, "speech recognition accuracy" directly affects "interaction fluency"). Therefore, this study adopts the DEMATEL method to analyze the causal relationships among the criteria. By calculating centrality and cause degree, it is possible not only to determine the comprehensive weight of each criterion, but also to identify which ones are the "causal factors" driving the entire system and which ones are the passive "result factors," thereby uncovering the inherent logic of design optimization.

Third Stage: Optimal Design Scheme Selection Based on VIKOR

After determining the indicator weights, the final stage involves ranking the alternative design schemes using the VIKOR method. The core advantage of the VIKOR method is its ability to find a "compromise solution," that is, to strike the closest balance between conflicting criteria (such as "high performance" and "low cost," or "multi-functionality" and "ease of use"). By calculating the group utility value and the individual regret value, the most suitable elderly companion robot design concept for current market needs is ultimately determined.

In summary, this hybrid framework provides a systematic and objective scientific basis for design decisions regarding companion robots for the elderly through a closed-loop process of "fuzzified input—causal analysis—trade-off ranking output." [4]

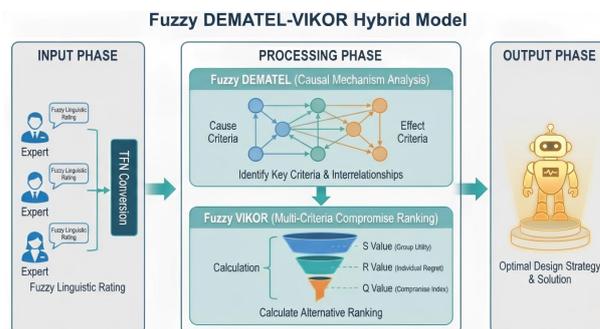


Fig. 1. The proposed hybrid decision-making framework for elderly companion robot design

B. Fuzzy DEMATEL for Causal Relationship Analysis

In order to identify the complex causal relationships among the design elements of companion robots for the elderly in a fuzzy environment, this study adopts the Fuzzy DEMATEL method. This approach combines the advantages of fuzzy set theory in handling semantic ambiguity with the capability of the DEMATEL method to analyze system structures.

1) Preliminaries of Fuzzy Set Theory

In complex systems involving the needs assessment and design decisions for older adults, evaluation information often contains a great deal of subjectivity and uncertainty. Decision-makers (experts or users) usually find it difficult to express their preferences with precise numerical values and are more inclined to use linguistic variables such as "very important" or "average." To effectively handle this fuzziness, this study introduces fuzzy set theory and converts linguistic

variables into triangular fuzzy numbers (TFNs) for quantitative calculations [5].

A triangular fuzzy number is a special type of fuzzy number that is widely used due to its high computational efficiency and its ability to closely fit human semantic judgments. Define the fuzzy number as a triangular fuzzy number on \mathbb{R} , denoted as \tilde{A} , where $\tilde{A} = (l, m, u)$. The parameters l , m , and u represent the lower bound, the median, and the upper bound of the fuzzy number, respectively. The membership function is defined as follows:

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x < l \\ \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m < x \leq u \\ 0, & x > u \end{cases} \quad (1)$$

Among them, $\mu_{\tilde{A}}(x)$ represents the degree to which element x belongs to fuzzy set \tilde{A} . When $\mu_{\tilde{A}}(x) = 1$, this fuzzy number degenerates into a precise numerical value.

In order to perform aggregation operations in the DEMATEL and VIKOR models, suppose there are two triangular fuzzy numbers, $\tilde{A}_1 = (l_1, m_1, u_1)$ and $\tilde{A}_2 = (l_2, m_2, u_2)$, and a positive real number k . The basic algebraic operational rules (See formulas (2), (3), (4), (5)) are as follows:

Addition

$$\tilde{A}_1 \oplus \tilde{A}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad (2)$$

Subtraction

$$\tilde{A}_1 \ominus \tilde{A}_2 = (l_1 - u_2, m_1 - m_2, u_1 - l_2) \quad (3)$$

Multiplication

$$\tilde{A}_1 \otimes \tilde{A}_2 \approx (l_1 l_2, m_1 m_2, u_1 u_2) \quad (4)$$

(Note: It is assumed here that the fuzzy number is positive, i.e., $l_1, l_2 \geq 0$)

Scalar Multiplication

$$k \times \tilde{A}_1 = (kl_1, km_1, ku_1), \quad k > 0 \quad (5)$$

Through the above definitions, this study establishes a bridge for converting qualitative language into quantitative mathematical models. In the subsequent evaluation process, all experts' ratings of the design criteria (as shown in Table 1) will be strictly converted into TFNs according to the above rules, to ensure the objectivity and scientific validity of the analysis results.

TABLE I. DESIGN CRITERIA SCORING

Linguistic Variable	Influence Score	TFN (l, m, u)
Very Low Influence (VL)	0	(0, 0, 0.25)
Low Influence (L)	1	(0, 0.25, 0.5)
Medium Influence (M)	2	(0.25, 0.5, 0.75)
High Influence (H)	3	(0.5, 0.75, 1.0)
Very High Influence (VH)	4	(0.75, 1.0, 1.0)

2) The Procedure of Fuzzy DEMATEL

Based on the above fuzzy theory, the specific implementation steps of Fuzzy DEMATEL are as follows:

Step 1: Construct the Fuzzy Direct-Relation Matrix

Let k be the number of experts. The k -th expert evaluates the direct influence of criterion C_i on C_j and obtains the fuzzy evaluation $\tilde{x}_{ij}^k = (l_{ij}^k, m_{ij}^k, u_{ij}^k)$. By aggregating the opinions of all experts using the averaging method, the initial fuzzy direct influence matrix \tilde{Z} is constructed:

$$\tilde{Z} = [\tilde{z}_{ij}]_{n \times n}, \quad \text{where } \tilde{z}_{ij} = \frac{1}{k} \sum_{k=1}^K \tilde{x}_{ij}^k \quad (6)$$

Step 2: Normalize the Direct-Relation Matrix

To standardize the data dimensions, matrix \tilde{Z} is normalized to obtain the standardized fuzzy matrix \tilde{X} :

$$\tilde{X} = S \times \tilde{Z}, \quad S = \frac{1}{\max_{1 \leq i \leq n} \sum_{j=1}^n u_{ij}} \quad (7)$$

where u_{ij} is the upper bound of the triangular fuzzy number.

Step 3: Compute the Total Relation Matrix

By applying the principle of matrix series, when $n \rightarrow \infty$, $\tilde{X}^n \rightarrow 0$. Comprehensive Impact Matrix \tilde{T} capturing both direct and indirect effects. As shown below:

$$\tilde{T} = \tilde{X}(I - \tilde{X})^{-1} \quad (8)$$

In this step, the elements $\tilde{t}_{ij} = (l^{ij}, m^{ij}, u^{ij})$ in matrix \tilde{T} are also triangular fuzzy numbers. For ease of subsequent analysis, these need to be defuzzified, typically using the CFCS (Converting Fuzzy data into Crisp Scores) method or the simple centroid method to convert them into crisp values t_{ij} .

Step 4: Calculate Prominence and Relation

Based on the defuzzified total influence matrix T , calculate the "degree of influence" (D) and "degree of being influenced" (R) for each indicator:

$$D_i = \sum_{j=1}^n t_{ij}, \quad R_i = \sum_{j=1}^n t_{ji} \quad (9)$$

Based on this, two key analytical vectors are defined:

Prominence ($P_i = D_i + R_i$): Indicates the importance of indicator i within the entire system. The greater the value, the more crucial the design element.

Relation ($E_i = D_i - R_i$): Indicates the causal attribute of indicator i .

If $E_i > 0$, then this indicator is a causal factor (Cause Group), tending to influence other indicators and serving as the driving force for design optimization.

If $E_i < 0$, then this indicator is a result factor (Effect Group), and tends to be influenced by other indicators.

By constructing a coordinate system ($D+R, \check{v} - B$), a causal relationship diagram, the key driving factors in the design of companion robots for the elderly (such as "safety") and the ultimate desired outcomes (such as "emotional attachment") can be intuitively identified.

C. VIKOR for Compromise Solution Selection

After determining the relative importance of each evaluation criterion for elderly companion robots, this study uses the VIKOR method to rank the alternative design schemes. VIKOR is a compromise ranking method based on multi-criteria optimization. Unlike methods that emphasize the "optimal" choice, the core idea of VIKOR is to find a "compromise solution"—that is, within mutually conflicting evaluation criteria (for example, Scheme A has high safety but weak interaction, while Scheme B offers good interaction but has a steep learning curve), it seeks to strike a balance that both maximizes group utility and minimizes individual regret [6].

The geometric meaning of the VIKOR method is shown in Figure 2; it evaluates alternatives by measuring their distance from the "positive ideal solution."

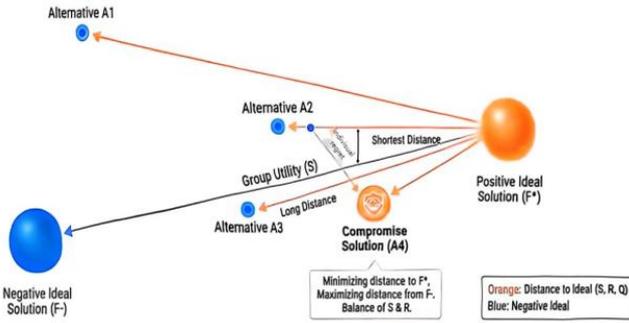


Fig. 2. The Geometric interpretation of the VIKOR method.

Assume there are m (A_1, A_2, \dots, A_m) alternatives and n (C_1, C_2, \dots, C_n) criteria. First, determine the optimal value (positive ideal solution f_i^*) and the worst value (negative ideal solution f_i^-) for each criterion:

$$f_i^* = \max_j f_{ij} \quad (10)$$

$$f_i^- = \min_j f_{ij} \quad (11)$$

Among them, f_{ij} represents the evaluation value of the j -th alternative on the i -th criterion (the precise value obtained after defuzzification of the fuzzy number). For benefit-type criteria (the larger, the better), the maximum value is taken as the ideal solution; for cost-type criteria (the smaller, the better), the opposite applies.

Step 2: Calculate Group Utility and Individual Regret

Introduce the indicator weights w_i obtained from the previous stage of DEMATEL to calculate the group (A_j) utility value (S_j) and individual regret value (R_j) for each scheme:

$$S_j = \sum_{i=1}^n w_i \frac{(f_i^* - f_{ij})}{(f_i^* - f_i^-)} \quad (12)$$

$$R_j = \max_i [w_i \frac{(f_i^* - f_{ij})}{(f_i^* - f_i^-)}] \quad (13)$$

S_j (Group Utility): Represents the overall performance across all indicators, reflecting the satisfaction of "most" criteria. The smaller the S_j , the better the overall benefit.

R_j (Individual Regret): Represents the level of regret for the weakest indicator, reflecting the dissatisfaction of the "opponent." The smaller the R_j , the less inadequate the proposal is in its weakest area.

Step 3: Compute the Compromise Index Q

Finally, by integrating the S value and R value, the comprehensive benefit index for each scheme is calculated:

$$Q_j = v \frac{(S_j - S^-)}{(S^+ - S^-)} + (1-v) \frac{(R_j - R^-)}{(R^+ - R^-)} \quad (14)$$

Among them:

$$S^+ = \min_j S_j, \quad S^- = \max_j S_j \quad (15)$$

$$R^+ = \min_j R_j, \quad R^- = \max_j R_j \quad (16)$$

v is the decision mechanism coefficient, usually set to 0.5. When $v > 0.5$, decisions tend to "maximize group utility"; when $v < 0.5$, decisions tend to "minimize individual regret."

Step 4: Ranking and Compromise Solution

Sort the alternatives in ascending order based on the Q value. The alternative ranked first (with the smallest Q value) is considered the best compromise solution. This solution must satisfy the following two conditions simultaneously to be regarded as the unique optimal solution; otherwise, a set of compromise solutions will be generated. Dominance Condition: $Q(A^{(2)}) - Q(A^{(1)}) \geq 1/(m-1)$, where $A^{(1)}$ and $A^{(2)}$ represent the first and second ranked alternatives, respectively; Stability Condition: the alternative $A^{(1)}$ must also rank among the top positions in the S value or R value sorting.

Through this process, this study is able to identify design solutions for companion robots for the elderly that achieve the optimal balance between "functionality" and "emotionality."

III. EMPIRICAL ANALYSIS

A. Analysis of Design Criteria via DEMATEL

To identify the intrinsic dependencies among the design elements of companion robots for the elderly, this study employs the Fuzzy DEMATEL-VIKOR framework, which is a decision-making methodology based on expert knowledge rather than large-scale user surveys. To conduct the evaluation, an expert panel consisting of 6 domain specialists was established. These experts were invited to perform pairwise comparisons of the evaluation criteria based on their professional experience in relevant fields [7].

1) Design Criteria Description

Based on literature review and preliminary research, this study has identified the following key design principles (See Figure 3):

C1 Safety & Reliability: Involves privacy protection, fall prevention monitoring, and system stability.

C2 Ease of Use: Learning curve of operation and interface intuitiveness.

C3 Interaction Capability: Speech recognition accuracy

and multimodal response speed.

C4 Emotional Intelligence: Empathy expression and emotional companionship functions.

C5 Cost Performance: Purchase cost and maintenance expenses.

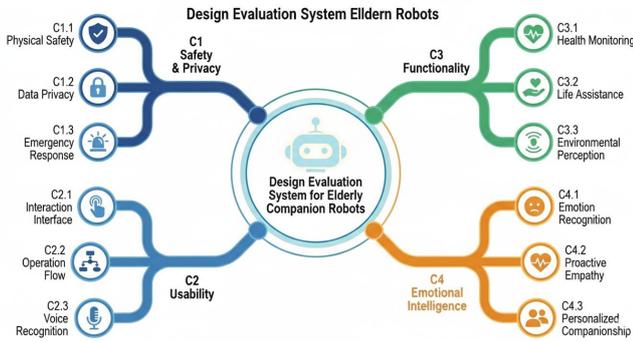


Fig. 3. Design criteria description.

2) Total Relationship Analysis

According to the steps described in Section 2.2, the expert ratings are first converted into triangular fuzzy numbers, and after defuzzification, the comprehensive influence matrix T is obtained. Subsequently, the influence degree (D) and the influenced degree (R) of each indicator are calculated, and the results are shown in Table 2.

TABLE II. PROMINENCE AND RELATION OF DESIGN CRITERIA.

Criteria	Influence (D)	Influenced (R)	Prominence (D+R)	Relation (D-R)	Role
C1 Safety & Reliability	3.842	2.115	5.957	1.727	Cause (Core Driver)
C2 Ease of Use	2.956	3.012	5.968	-0.056	Effect
C3 Interaction	3.125	3.45	6.575	-0.325	Effect
C4 Emotional Intelligence	2.684	4.31	6.994	-1.626	Effect (Core Outcome)
C5 Cost Performance	2.45	2.17	4.62	0.28	Cause

B. Ranking of Design Alternatives via VIKOR

Based on the indicator weights derived from the previous stage of DEMATEL analysis (i.e., the proportion of centrality for each indicator), this study further employs the VIKOR method to rank and optimize four representative design concepts for elderly companion robots.

1) Definition of Alternatives

To cover the mainstream design directions in the market as well as potential innovative combinations, this study has developed the following four alternative schemes (as shown in Table 3):

TABLE III. FOUR SOLUTIONS

Type code	Type Name	Features	Disadvantages
A1	Security Monitoring-Oriented	Focuses on C1 (safety), equipped with high-precision lidar and medical-grade fall detection, emphasizing all-	Interactions are stiff and lack emotional warmth, which can easily give

Type code	Type Name	Features	Disadvantages
A2	Deep Emotional Interaction	weather physical monitoring. Focuses on C4 (emotional intelligence) and C3 (interaction capabilities), featuring human-like facial expressions and an advanced NLP dialog system.	elderly people a sense of being monitored. Physical security features are relatively weak, and high computing power results in higher costs.
A3	Life Function Support Type	Focusing on C2 (ease of use) and C5 (cost-effectiveness), it mainly features practical functions such as medication reminders and home appliance control, similar to a mobile smart speaker. Design based on "causal discovery" using DEMATEL. Set C1 (safety features) as an invisible underlying layer, while enhancing C4 (emotional experience) in explicit interactions. In other words, "a warm appearance with safety at its core."	Lack of deep emotional connection and proactive safety intervention capabilities.
A4	Balanced Hybrid		-

2) VIKOR evaluation results

The expert panel was invited to score the performance of the four schemes above under five evaluation criteria. After processing with fuzzy numbers and defuzzification, the group utility value (S), individual regret value (R), and compromise benefit value (Q) of each scheme were calculated using the formulas described in Section 2.3. In the calculation, the decision mechanism coefficient is set to achieve a balance between maximizing group utility and minimizing individual regret. The calculation results are shown in Table 4.

TABLE IV. S, R, AND Q VALUES FOR THE FOUR ALTERNATIVES.

Alternatives	S (Group Utility)	R (Individual Regret)	Q (Compromise Index)	Ranking
A1 (Safety-Centric)	0.685	0.42	0.741	3
A2 (Emotional)	0.354	0.21	0.312	2
A3 (Functional)	0.792	0.65	1	4
A4 (Hybrid)	0.115	0.085	0.062	1

3) Results Discussion and Optimal Solution Determination

As shown in Figure 4, a comparative analysis of the scores for each scheme is conducted:

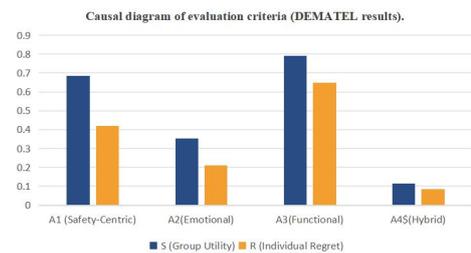


Fig. 4. Causal diagram of evaluation criteria (DEMATEL results).

Optimal solution analysis:

Option A_4 (Hybrid) has the lowest Q value (0.062), which is significantly lower than the second-ranked option A_2 (0.312). The advantage verification: $DQ=Q(A_2)-Q(A_4)=0.312 - 0.062 = 0.250$.

Although this value is slightly below the strict threshold ($DQ \leq 0.33$), Option A_4 consistently ranks first in both Group Utility (S) and Individual Regret (R $\$$) metrics (satisfying the Stability Condition). Therefore, considering its comprehensive dominance, A_4 is identified as the optimal compromise solution, while A_2 serves as an alternative backup.

Conclusion:

A_4 is the only optimal compromise solution. This indicates that simply piling on security features (such as A_1) or excessively pursuing emotional anthropomorphism (such as A_2) are not the best strategies. The ideal design should be one that, while meeting the highly weighted "driving factor" (security), also maximizes the "outcome factor" (emotional experience).

Suboptimal solution and inferior solution:

A_2 (Emotional) Ranked second, indicating that users' desire for emotional interaction is second only to basic safety needs. A_3 (Functional) Performed the worst, which may be related to the severe homogeneity of existing low-end products on the market and their inability to address the deep sense of loneliness among the elderly.

This result provides a direct quantitative basis for subsequent design optimization strategies.

IV. DISCUSSION AND OPTIMIZATION STRATEGIES

A. The Causal Mechanism of Trust and Acceptance

The results of the empirical analysis (particularly the causal relationship diagram in DEMATEL) reveal a unique psychological mechanism among elderly user groups: in human-computer interaction, trust is not only a product of emotional attachment, but also a prerequisite for it[8].

1) Safety as the Foundation of Trust

DEMATEL analysis shows that (Safety & Reliability) has the highest positive causal degree, clearly identifying it as the core driving factor of the system. This finding challenges the view in some existing studies that overemphasizes "anthropomorphic appearance" or "entertainment functions." For elderly individuals in a period of physical and mental decline, fear of technology and concerns about privacy breaches are the main psychological barriers. Recent empirical studies have also confirmed that safety is a decisive antecedent condition for elderly users' satisfaction with home care devices, and its absence triggers immediate dissatisfaction [9]. Therefore, physical safety and data privacy constitute the "underlying logic" of user acceptance. If robots exhibit any instability (such as falsely reporting falls, mistakenly activating late at night, or unclear data privacy), elderly users will quickly become defensive and subsequently reject any deep emotional interactions. Therefore, physical safety and data privacy constitute the "underlying logic" for user acceptance.

2) The Dependency of Emotional Interaction

On the other hand, (Emotional Intelligence), although it has the highest centrality (indicating its utmost importance), has a negative causality value, making it a typical "result factor." This suggests that emotional experiences do not arise independently, but are highly dependent on the fulfillment of other functions. Only after "basic security needs" and "intermediate usability needs" (have been met does the higher-level "emotional resonance" become possible. This hierarchical structure is similar to Maslow's hierarchy of needs: companionship without a sense of security is ineffective, or even harmful.

3) Comparison with Literature

Previous research on social assistive robots (SARs) has often focused on enhancing affinity through facial expressions or voice intonation. However, the VIKOR ranking results of this study (with hybrid types outperforming purely emotional types) further confirm that mere emotional simulation, if lacking reliable functional support, can only provide a brief sense of novelty and cannot sustain long-term user engagement. True "acceptance" arises when users are convinced that the device is a reliable guardian in their lives.

In summary, the design of companion robots for the elderly should follow a causal path (see figure 5) that "begins with safety and ends with emotional connection."



Fig. 5. The "Pyramid of Trust" Model for Elderly Companion Robots

B. Strategic Priorities for Robot Design

Based on the optimal results of the VIKOR model (the Q value of scheme is the lowest) and the causal logic revealed by DEMATEL, this study proposes three core design optimization strategies for elderly companion robots. These strategies aim to address the current product pain point of "fragmented functions" and to build an intelligent ecosystem that integrates safety, ease of use, and emotional support (as shown in Figure 6). [10]

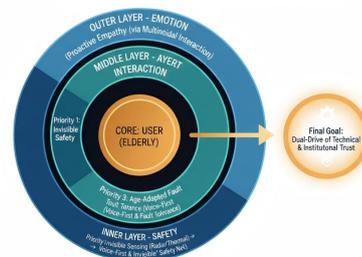


Fig. 6. Layered optimization strategy model (onion model).

Target audience: Core driving factors in DEMATEL (C_1 Safety & Reliability, high causality degree).

Although security is the cornerstone of the system, an excessive "sense of surveillance" can create resistance among the elderly. Therefore, design strategies should shift from "overt monitoring" to "invisible protection."

Non-intrusive sensing: Instead of the traditional method of continuous camera recording, this approach uses millimeter-wave radar or thermal imaging technology for fall detection and vital sign monitoring. This not only protects user privacy (by capturing only point clouds or heat-maps instead of optical images), but also effectively reduces users' psychological resistance.

Environmental intelligence integration: Embedding safety features beneath everyday interactions. For example, when a robot detects that an elderly person is walking unsteadily, it should not emit a harsh alarm, but instead proactively approach and ask, "Would you like me to contact your family for a chat?" In this way, gentle and caring language is used to mask the more rigid process of health monitoring.

Priority 2: Proactive Empathy via Multi-modal Interaction

Target object: The factor with the highest centrality in DEMATEL (C_4 Emotional Intelligence, high centrality).

The VIKOR results show that users reject cold, purely functional machines. To improve acceptance, design must shift from "command-responsive" to "proactively empathetic."

Multi-modal emotion recognition: The system should not rely solely on voice recognition, but also incorporate facial expression analysis and intonation-based emotion detection. When an elderly person furrows their brows or speaks slowly, the robot should be able to recognize a "sad" emotion and automatically switch to a gentle voice mode.

Active Interaction Mechanism: Breaking the traditional logic of "user initiation." For example, after a long period of silence, the robot should proactively start a conversation ("The weather is nice today; would you like to listen to some opera?") to simulate the companionship of a real family member and help alleviate the loneliness of elderly people living alone.

Technological Implementation of Emotional Intelligence: To ensure the practical feasibility of the "Emotional Intelligence" (C_4) strategy, the proposed robot employs a Multimodal Affective Computing Architecture. Unlike basic pre-programmed responses, this system integrates three key layers:

- **Perception Layer (Multimodal Fusion):** The system combines acoustic features from speech (e.g., pitch, tone) via microphones with facial expression analysis (FACS) via cameras. This multimodal fusion improves the accuracy of recognizing complex elderly emotions, such as "anxiety" or "depressed mood," which are often subtle.
- **Decision Layer (Cognitive Appraisal):** Based on the OCC (Ortony, Clore, and Collins) Model, the robot processes perceptual inputs to appraise the user's emotional state. This ensures that the robot's feedback

(voice comfort or playing music) is contextually appropriate rather than random.

- **Long-term Engagement Mechanism:** To maintain interest over time, the system incorporates an Episodic Memory Module. This module logs interaction history and user preferences. If the data shows a user frequently expresses loneliness in the evenings, the robot will proactively initiate conversation during those specific time windows, shifting the interaction paradigm from "passive response" to "proactive companionship."

Priority 3: Age-Adapted Fault Tolerance

Target: Individual regret value in VIKOR.

For high-risk points in (C_2 usability) that may cause users to abandon the product, strategies should focus on "zero learning cost."

Voice Priority and Automatic Error Correction: Considering the decline in finger dexterity among the elderly, the interactive interface should prioritize voice input, with touch as a supplementary option. At the same time, fuzzy semantic understanding technology should be introduced so that when seniors express themselves unclearly or give incorrect commands, the system can infer their intentions from the context (for example, understanding "turn on that hot thing" as "turn on the heater") instead of repeatedly reporting errors.

Personified feedback: Use nodding, blinking, or simple body movements instead of complex on-screen text prompts to reduce cognitive load.

C. System Implementation Architecture

To validate the feasibility of the prioritized strategies without an immediate physical prototype, we designed a "Dual-Loop" System Architecture (see Figure 7) that translates the "Safety-First" principle into engineering logic. The system comprises two parallel processing loops:

- **The Safety Loop (High-Priority):** This kernel-level loop processes data from millimeter-wave radars and IMU sensors. Unlike cameras, radars preserve user privacy while enabling all-weather monitoring. This loop runs a real-time Fall Detection Algorithm. Once a hazard is detected, it triggers an "Emergency Override" signal.
- **The Emotion Loop (Normal-Priority) :** This application-level loop handles multimodal interaction. It fuses visual data (Facial Expression) and audio data (Tone/Pitch) to feed the OCC Cognitive Model, generating empathetic feedback to alleviate loneliness .
- **Priority arbitration mechanism:** A crucial feature is the hardware interrupt logic. As shown by the red arrow in Figure 7, the Safety Loop has higher authority than the Emotion Loop. For instance, if a fall is detected while the robot is playing music or chatting, the Safety Loop immediately interrupts the Emotion Loop, silencing the entertainment function to execute the emergency call protocol. This architecture ensures that the "functional reliability" (C_1) strictly precedes "emotional

interaction," technically strictly adhering to the DEMATEL causal analysis results.

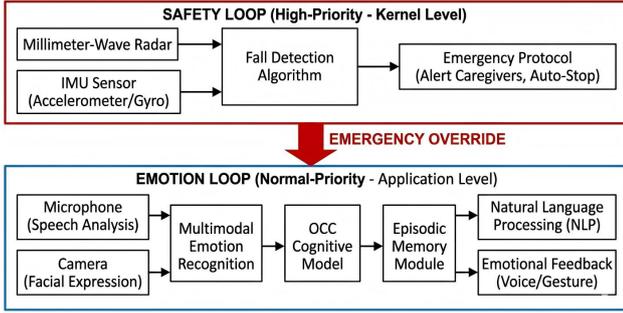


Fig. 7. The proposed "Dual-Loop" System Architecture.

D. Comparative Analysis with Market

Benchmarks To validate the superiority of the optimized strategy, we conducted a theoretical benchmark comparison against leading market products: Paro (Therapeutic Robot) and Sony Aibo (Entertainment Robot) (as shown in Table 5).

TABLE V. COMPARATIVE ANALYSIS OF (HYBRID) VS. MARKET LEADERS.

Feature	Paro (Therapeutic)	Sony Aibo (Entertainment)	Proposed A4 (Hybrid Guard)
Primary Goal	Calming dementia patients	Playfulness & Pet simulation	Safety Assurance + Companionship
Safety Sensing	None (Passive interaction)	Basic obstacle avoidance	Radar/Lidar + Fall Detection (Priority 1)
Interaction	Tactile (Fur sensors)	Barking, movement, OLED eyes	Voice-First + Emotional Feedback
Limitations	No emergency response; expensive	Low utility for frail elderly	High complexity integration
Suitability	Nursing homes only	Active healthy seniors	Aging-in-place (Home Care)

Analysis: While Paro excels in emotional comfort and Aibo in dynamic interaction, both lack the critical safety layer required for independent living. The strategy addresses this gap by embedding an 'invisible sensing' layer that operates independently of the emotional module, ensuring that in the event of a fall, the robot transitions from a 'pet' to a 'guardian'.

E. Implications for Industry and Policy

Based on the empirical findings of the Fuzzy DEMATEL-VIKOR model, this study not only offers micro-level guidance for the development of individual products, but also provides an important theoretical foundation for the macro-level development of the elderly welfare technology industry and the formulation of related policies.

1) For Industry: From "Feature Stacking" to "Modular Trust"

Empirical data indicates that users have significant hierarchical differences in their needs for "security" (driving factor) and "emotional engagement" (result factor). Therefore, in product iteration, companies should abandon the strategy of piling on all-encompassing features and

instead adopt a modular architecture of a "security core + emotional shell."

Privacy by Design: Given the high importance of (security), manufacturers should incorporate data privacy protection at the initial stage of product development, rather than adding it later as a patch. It is recommended that the industry establish a unified "Senior Data Security Standard." Sensitive data collected by cameras and microphones must be desensitized locally, rather than being uploaded directly to the cloud, in order to eliminate the "technological anxiety" experienced by elderly users.

Standardization of Affective Computing Interfaces: Given the advantages of (hybrid), it is recommended that the industry open up affective computing API interfaces, allowing third-party developers to build diverse affective interaction applications (such as dialect companion chat or opera companionship) on a solid "security foundation," thereby meeting the personalized needs of elderly individuals from different cultural backgrounds at low cost.

2) For Policy: Certification Standards and Inclusion in Care Insurance

Government regulatory authorities should adjust their support policies for smart elderly care devices based on the causal mechanisms of user acceptance.

Establish a tiered certification system: Current industry standards mainly focus on electrical safety and lack regulations addressing "psychological safety" and "age-friendly interaction." It is recommended that regulatory authorities refer to the evaluation index system presented in this study to establish a tiered certification system for elder care companion robots. Only products that have passed dual certification for "privacy safety" and "emotional interaction effectiveness" should be awarded the "age-friendly product" label.

Inclusion in Long-Term Care Insurance (LTCI): Research has shown that high-quality companion robots (such as those in this program) can effectively alleviate the psychological stress of elderly people living alone and have potential medical value in preventing cognitive impairment. Therefore, policymakers should consider including certified companion robots in the list of assistive devices eligible for long-term care insurance rentals or granting government procurement subsidies. This would lower the threshold for elderly families to use these devices and promote the large-scale development of the smart elderly care industry [11].

In summary, building a healthy ecosystem for elderly care robots requires the dual drivers of "technological trust" and "institutional trust" (as shown in Figure 8).



Fig. 8. Eco-system Framework for Trustworthy Elderly Companion Robots.

V. CONCLUSION

A. Summary of Findings

In light of the difficulty in balancing "functionality and emotion" in the design of companion robots against the backdrop of an aging population, this study constructs a hybrid decision-making model based on Fuzzy DEMATEL-VIKOR and conducts a systematic empirical analysis. The main contributions and findings of the research are summarized as follows:

- Constructed a quantitative design decision-making framework: This study successfully introduced fuzzy set theory to address the subjectivity and uncertainty of user needs, solving the problem of distortion in traditional questionnaires when capturing the ambiguous semantics of the elderly (such as "slightly unsafe"). This framework provides a scientific path from qualitative evaluation to quantitative optimization for the design of aging-friendly products.
- Revealed the causal mechanism of "trust first": Causal analysis shows that "safety and reliability (" has the highest positive causality () and is the core driving force behind user acceptance, where as "emotional intelligence (" has the highest centrality but a negative causality, making it a result factor. This finding quantitatively confirms the hypothesis that "safety is the prerequisite for emotion"—that is, elderly users will only develop deep emotional attachment once they are assured that their physical and privacy security is protected.
- "Hybrid Balance" identified as the optimal design strategy (Based on VIKOR): Among the compromise rankings of the four alternatives, the Hybrid Balance (solution emerged as the sole optimal solution with the lowest Q value (0.062), significantly outperforming purely emotional (or functional (types. This suggests that the ideal product form should be an organic combination of an "invisible safety net" and "explicit emotional interaction"—that is, using non-intrusive technologies such as millimeter-wave radar at the foundational level to ensure safety, while providing high emotional intelligence companionship through multi-modal interaction at the surface level.

B. Limitations and Future Work

Although this study provides effective theoretical support for the design of companion robots for the elderly, there are still the following limitations that need to be addressed in future work.

Limitations in sample size and cultural differences: The empirical data in this study mainly come from the evaluations of 10 field experts and some elderly users. Although the DEMATEL method exhibits good robustness with small samples, the limited sample size may result in biased outcomes. In addition, elderly individuals from different cultural backgrounds (such as collectivist versus

individualist cultures) may have varying definitions of "privacy" and "companionship."

Future research should expand the sample size and incorporate cross-cultural comparative studies to explore differences in design priorities across diverse cultural contexts, thereby enhancing the generalizability of the model.

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