Service Quality Evaluation of Integrated Medical and Elderly Care Institutions Based on TIFN-CPT Approach

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Abstract: As global population aging intensifies, constructing a scientific evaluation system for Integrated Medical and Elderly Care service quality has emerged as a vital strategy. To address the inherent fuzziness in evaluations and the risk preferences of decision-makers, this paper proposes a multi-criteria group decision-making approach integrating Triangular Intuitionistic Fuzzy Numbers and Cumulative Prospect Theory. First, an evaluation criteria system is established across five core dimensions: life care, cultural and recreational service, medical nursing, rehabilitation and health care, and spiritual comfort. Second, the Bidirectional Projection method is utilized to transform TIFN evaluation data into connection degrees, which are then aggregated using the Connection Degree Weighted Averaging operator. Subsequently, CPT is introduced to characterize the behavioral features of decision-makers regarding gains and losses, facilitating the calculation of overall prospect values. Empirical results indicate that medical nursing and rehabilitation are the decisive dimensions for service quality, with Institution A_2 identified as the optimal choice due to its superior performance in these areas. This study provides a rigorous decision-making framework for quality supervision and resource optimization in IMEC institutions.

Keywords: Integrated Medical and Elderly Care; Service Quality Evaluation; Triangular Intuitionistic Fuzzy Numbers; Cumulative Prospect Theory

1. Introduction

As the aging population intensifies globally and particularly in China, the limitations of traditional elderly care models in coordinating medical care, rehabilitation, and daily life support have become increasingly apparent. Consequently, promoting the organic integration of medical and elderly care resources to construct an "Integrated Medical and Elderly Care" service system has emerged as a vital strategy for active aging [1]. According to data from the Seventh National Population Census of China, the population aged 60 and above has exceeded 264 million, with those aged 65 and above surpassing 190 million. Against this backdrop, a scientific evaluation of the service quality in IMEC institutions is essential, as it helps identify weaknesses in service provision and provides a basis for optimizing resource allocation and enhancing service levels. Since such evaluations typically involve multiple stakeholders making comprehensive judgments on various alternatives across multiple criteria—accompanied by significant amounts of fuzzy and incomplete information—the process essentially constitutes a typical Multi-Criteria Group Decision-Making problem [2].

Existing research indicates that fuzzy multi-criteria decision-making theory provides effective tools for handling uncertain information in complex evaluation problems. From classical fuzzy sets to intuitionistic fuzzy sets and subsequently to triangular intuitionistic fuzzy sets, the representation of fuzzy information has continuously expanded, allowing decision-making data to characterize the cognitive features of evaluators in greater detail [3]. Current studies on TIF-MCGDM primarily achieve alternative ranking through aggregation operators, score functions, or methods such as TOPSIS, laying the foundation for methodological development [4]. In the field of IMEC, existing studies have focused on service model analysis, development challenges, the construction of evaluation indicator systems, and the application of evaluation methods, resulting in the establishment of various indicator frameworks and assessment tools [5,6]. However, two major gaps remain in the current literature. First, the theoretical framework for TIF-MCGDM is not yet fully comprehensive, particularly regarding methods for group decision analysis based on decision matrices, which still require further exploration. Second, research on service quality evaluation for IMEC institutions often emphasizes indicator construction and the application of traditional evaluation techniques, while paying insufficient attention to fuzzy information processing and decision-makers' risk preferences. This leads to evaluation results that may lack behavioral consistency and practical alignment.

To address these issues, this paper introduces Cumulative Prospect Theory into the TIF-MCGDM framework to develop a MCGDM approach for evaluating the service quality of IMEC institutions. The study first establishes a service quality evaluation indicator system. Subsequently, TIFNs are utilized to express expert evaluation information. Building upon the aggregation of group evaluation data, CPT is integrated for a comprehensive assessment. Finally, the feasibility and effectiveness of the proposed method are verified through an empirical analysis, based on which suggestions for service quality improvement are provided.

2. Service Quality Evaluation Criteria for IMEC Institutions

Existing studies on the service quality evaluation of IMEC institutions have mainly focused on the construction of indicator systems from different perspectives [7]. Some studies developed evaluation frameworks based on the SPO model, emphasizing that service quality should be assessed from structural conditions, service processes, and service outcomes [8]. Other studies, drawing on SERVQUAL or SERVPERF, paid more attention to elderly residents' actual service experience and service perception [9]. In addition, relevant research has shown that the service quality of IMEC institutions should not only reflect basic elderly care functions, but also incorporate medical support, rehabilitation, health management, and psychological care [10]. Although the indicator systems proposed in previous studies differ in form and scope, their core concerns are relatively consistent. In general, the existing literature repeatedly highlights daily care, cultural support, medical and nursing services, rehabilitation and health care, and spiritual or emotional comfort as the key dimensions in evaluating service quality [9]. Therefore, rather than directly adopting a large and complex indicator system, this study extracts the most representative dimensions from prior studies and builds a concise evaluation criteria system consisting of five core attributes, namely life care, cultural and recreational service, medical nursing service, rehabilitation and health care service, and spiritual comfort service. The specific composition and connotation of the evaluation criteria system are shown in Table 1. These five attributes can effectively reflect the essential service content of IMEC institutions and provide a clear basis for the subsequent evaluation model.

Table 1. Service Quality Evaluation Criteria for IMEC Institutions

Attribute	Criterion	Meaning
C1	Life Care	Daily living support and basic care for elderly residents.
C2	Cultural and Recreational Service	Cultural activities, leisure participation, and social interaction support.
C3	Medical Nursing Service	Medical treatment, nursing care, and health monitoring services.
C4	Rehabilitation and Health Care Service	Rehabilitation support, health management, and functional maintenance.
C5	Spiritual Comfort Service	Emotional support, psychological care, and humanistic concern.

Based on the above analysis, the service quality evaluation criteria adopted in this study are represented by five attributes, denoted as C_1-C_5. Compared with a highly detailed indicator system, this simplified framework is more suitable for the decision-making model developed in this paper, while still preserving the core dimensions repeatedly emphasized in the existing literature.

3. The Proposed Service Quality Evaluation Approach

3.1 Preliminaries

To effectively handle the fuzziness and behavioral psychological factors in the evaluation of IMEC institutions, this section introduces the basic definitions of TIFN numbers, connection degree theory, and CPT.

3.1.1 Triangular intuitionistic fuzzy numbers

Definition1. Let $\bar{A}$be a TIFN ion the real set R [11], expressed in parametric form as:

$$\bar{A}=\langle (a,b,c);\mu_{\bar{A}},\nu_{\bar{A}}\rangle \quad (1)$$

Where (a,b,c) represent the three scale values of the base, satisfying $a\leq b\leq c$; $\mu_{\bar{A}}$ denotes the maximum membership degree, $\nu_{\bar{A}}$ denotes the minimum non-membership degree, satisfying $0\leq\mu_{\bar{A}}\leq1$, $0\leq\nu_{\bar{A}}\leq1$, $0\leq\mu_{\bar{A}}+\nu_{\bar{A}}\leq1$. For a TIFN $\bar{A}$, its hesitation degree $\pi_{\bar{A}}$ represents the decision-maker's degree of uncertainty or abstention regarding the judgment, defined as $\pi_{\bar{A}}=1-\mu_{\bar{A}}-\nu_{\bar{A}}$.

Definition2. Suppose two TIFNs are $\bar{A}_1=\langle (a_1,b_1,c_1);\mu_{A_1},\nu_{A_1}\rangle$ and $\bar{A}_2=\langle (a_2,b_2,c_2);\mu_{A_2},\nu_{A_2}\rangle$, The Hamming distance between $\bar{A}_1$ and $\bar{A}_2$ is defined as[12]:

$$d_{TIFN}(\bar{A}_1,\bar{A}_2)=\frac{1}{6}\begin{bmatrix}\left|(1+\mu_{A_1}-\nu_{A_1})a_1-(1+\mu_{A_2}-\nu_{A_2})a_2\right|\\+\left|(1+\mu_{A_1}-\nu_{A_1})b_1-(1+\mu_{A_2}-\nu_{A_2})b_2\right|\\+\left|(1+\mu_{A_1}-\nu_{A_1})c_1-(1+\mu_{A_2}-\nu_{A_2})c_2\right|\end{bmatrix} \quad (2)$$

3.1.2 Bidirectional projection and transformation to connection degree

Definition 3. The Bidirectional Projection (BP) method for TIFNs. This method simultaneously considers both the magnitude and direction of vectors, allowing for a more accurate reflection of the proximity between two fuzzy numbers in multi-dimensional space. Let two TIFNs be defined as $\bar{A}_1=\langle (a_1,b_1,c_1);\mu_{A_1},\nu_{A_1}\rangle$ and $\bar{A}_2=\langle (a_2,b_2,c_2);\mu_{A_2},\nu_{A_2}\rangle$ Let their respective credibility adjustment factors be $\varphi_{\bar{A}_1}=1+\mu_{A_1}-\nu_{A_1}$ and $\varphi_{\bar{A}_2}=1+\mu_{A_2}-\nu_{A_2}$. The bidirectional projection measure $BP_{TIFN}(\bar{A}_1,\bar{A}_2)$ between $\bar{A}_1$ and $\bar{A}_2$ is defined as follows[13]:

$$BP_{TIFN}(\bar{A}_1,\bar{A}_2)=\frac{\sqrt{\varphi_{\bar{A}_1}^2(a_1^2+b_1^2+c_1^2)}\cdot\sqrt{\varphi_{\bar{A}_2}^2(a_2^2+b_2^2+c_2^2)}}{\sqrt{\varphi_{\bar{A}_1}^2(a_1^2+b_1^2+c_1^2)}\cdot\sqrt{\varphi_{\bar{A}_2}^2(a_2^2+b_2^2+c_2^2)}+J\cdot\left[\varphi_{\bar{A}_1}\varphi_{\bar{A}_2}(a_1a_2+b_1b_2+c_1c_2)\right]} \quad (3)$$

Where $BP_{TIFN}(\bar{A}_1,\bar{A}_2)$ is the bidirectional projection value between any two TIFNs $\bar{A}_1$ and $\bar{A}_2$, reflecting their degree of similarity; and $J=\left|\sqrt{\varphi_{\bar{A}_1}^2(a_1^2+b_1^2+c_1^2)}-\sqrt{\varphi_{\bar{A}_2}^2(a_2^2+b_2^2+c_2^2)}\right|$ represents the absolute difference between the magnitudes of the two TIFN models.

Definition 4. Transformation formulas for TIFNs. In the case where attribute values are represented as TIFNs, let the evaluation information provided by decision-maker D_k for alternative A_i under attribute C_j be $x_{ij}^k=\langle (a_{ij}^k,b_{ij}^k,c_{ij}^k);\mu_{ij}^k,\nu_{ij}^k\rangle$. Depending on the nature of attribute C_j, the Positive Ideal Point R_j^+ and the Negative Ideal Point R_j^- are defined as follows[14]:

If C_j is a benefit-type attribute ($C_j\in Be$), the Positive Ideal Point R_j^+ and the Negative Ideal Point R_j^- are:

$$R_j^+=\langle \left(\max_i a_{ij}^k,\max_i b_{ij}^k,\max_i c_{ij}^k\right);\max_i \mu_{ij}^k,\min_i \nu_{ij}^k\rangle=\langle \left(R_j^{1+},R_j^{2+},R_j^{3+}\right);\mu_j^+,\nu_j^+\rangle \quad (4)$$

$$R_j^-=\langle \left(\min_i a_{ij}^k,\min_i b_{ij}^k,\min_i c_{ij}^k\right);\min_i \mu_{ij}^k,\max_i \nu_{ij}^k\rangle=\langle \left(R_j^{1-},R_j^{2-},R_j^{3-}\right);\mu_j^-,\nu_j^-\rangle \quad (5)$$

If C_j is a cost-type attribute ($C_j\in Co$), the Positive Ideal Point R_j^+ and the Negative Ideal Point R_j^- are:

$$R_j^+=\langle \left(\min_i a_{ij}^k,\min_i b_{ij}^k,\min_i c_{ij}^k\right);\min_i \mu_{ij}^k,\max_i \nu_{ij}^k\rangle=\langle \left(R_j^{1+},R_j^{2+},R_j^{3+}\right);\mu_j^+,\nu_j^+\rangle \quad (6)$$

$$R_j^-=\langle \left(\max_i a_{ij}^k,\max_i b_{ij}^k,\max_i c_{ij}^k\right);\max_i \mu_{ij}^k,\min_i \nu_{ij}^k\rangle=\langle \left(R_j^{1-},R_j^{2-},R_j^{3-}\right);\mu_j^-,\nu_j^-\rangle \quad (7)$$

The formula for mapping the TIFN evaluation information x_{ij}^k to the connection degree $\theta\left(x_{ij}^k,R_j\right)_{TIFN}$ \$ in three-dimensional space is as follows [14]:

$$\theta\left(x_{ij}^k,R_j\right)_{TIFN}=a_{ij}^T\left(1-c_{ij}^T\right)+\left(1-a_{ij}^T-c_{ij}^T+2a_{ij}^Tc_{ij}^T\right)\tau+c_{ij}^T\left(1-a_{ij}^T\right)\varepsilon \quad (8)$$

Where a_{ij}^T and c_{ij}^T represent the identity degree and opposition degree between the attribute value x_{ij}^k and the ideal point R_j, respectively. Their specific substitution forms are:

(1) Identity Degree a_{ij}^T

Reflects the degree of consistency between x_{ij}^k and the Positive Ideal Point R_j^+:

$$a_{ij}^T=\frac{\varphi_{ij}^k\sqrt{\left(a_{ij}^k\right)^2+\left(b_{ij}^k\right)^2+\left(c_{ij}^k\right)^2}\cdot\varphi_j^+\sqrt{\left(R_j^{1+}\right)^2+\left(R_j^{2+}\right)^2+\left(R_j^{3+}\right)^2}}{\varphi_{ij}^k\sqrt{\left(a_{ij}^k\right)^2+\left(b_{ij}^k\right)^2+\left(c_{ij}^k\right)^2}\cdot\varphi_j^+\sqrt{\left(R_j^{1+}\right)^2+\left(R_j^{2+}\right)^2+\left(R_j^{3+}\right)^2}+J^+\cdot\varphi_{ij}^k\varphi_j^+\left(a_{ij}^kR_j^{1+}+b_{ij}^kR_j^{2+}+c_{ij}^kR_j^{3+}\right)} \quad (9)$$

(2) Opposition Degree c_{ij}^T

Reflects the degree of consistency between x_{ij}^k and the Negative Ideal Point R_j^-:

$$c_{ij}^{T}=\frac{\varphi_{ij}^{k}\sqrt{(a_{ij}^{k})^2+(b_{ij}^{k})^2+(c_{ij}^{k})^2}\cdot\varphi_j^{-}\sqrt{(R_j^{1-})^2+(R_j^{2-})^2+(R_j^{3-})^2}}{\varphi_{ij}^{k}\sqrt{(a_{ij}^{k})^2+(b_{ij}^{k})^2+(c_{ij}^{k})^2}\cdot\varphi_j^{-}\sqrt{(R_j^{1-})^2+(R_j^{2-})^2+(R_j^{3-})^2}+J^{-}\cdot\varphi_{ij}^{k}\varphi_j^{-}\left(a_{ij}^{k}R_j^{1-}+b_{ij}^{k}R_j^{2-}+c_{ij}^{k}R_j^{3-}\right)} \quad (10)$$

(3) Relevant Auxiliary Parameters

Confidence Adjustment Factors:

$$\varphi_{ij}^{k}=1+\mu_{ij}^{k}-\nu_{ij}^{k},\ \varphi_j^{+}=1+\mu_j^{+}-\nu_j^{+},\ \varphi_j^{-}=1+\mu_j^{-}-\nu_j^{-} \quad (11)$$

Absolute Differences of Model Magnitudes:

$$J^{+}=\left|\varphi_{ij}^{k}\sqrt{(a_{ij}^{k})^2+(b_{ij}^{k})^2+(c_{ij}^{k})^2}-\varphi_j^{+}\sqrt{(R_j^{1+})^2+(R_j^{2+})^2+(R_j^{3+})^2}\right| \quad (12)$$

$$J^{-}=\left|\varphi_{ij}^{k}\sqrt{(a_{ij}^{k})^2+(b_{ij}^{k})^2+(c_{ij}^{k})^2}-\varphi_j^{-}\sqrt{(R_j^{1-})^2+(R_j^{2-})^2+(R_j^{3-})^2}\right| \quad (13)$$

3.1.3 Connection degree weighted averaging (cdwa) operator

Definition 5. Let $\theta_k=a_k+b_k\tau+c_k\varepsilon$ be the connection degree provided by the k-th decision maker (k=1,2,…,m). Given the weight vector of decision makers $\lambda=(\lambda_1,\lambda_2,\ldots,\lambda_m)^T$, the CDWA operator is defined as[15]:

$$CDWA(\theta_1,\theta_2,\ldots,\theta_m)=\sum_{k=1}^{m}\lambda_k a_k+\left(\sum_{k=1}^{m}\lambda_k b_k\right)\tau+\left(\sum_{k=1}^{m}\lambda_k c_k\right)\varepsilon \quad (14)$$

By assigning specific values to the coefficients τ and ε (e.g., $\tau\in[-1,1]$ and ε=-1, the integrated connection degree can be converted into a deterministic crisp value x_{ij}, forming a real-number decision matrix.

3.1.4 Cumulative prospect theory

proposed by Tversky and Kahneman, is an effective behavioral decision theory for describing decision makers' risk preferences. Different from traditional rational decision models, CPT assumes that decision makers evaluate outcomes relative to a reference point and show asymmetric perceptions of gains and losses. In CPT, the prospect value of alternative A_i is determined by combining the value function and the weighting function, which can be expressed as[16]:

$$P_i=\sum_{j=1}^{n}\eta(\omega_j)v(x_{ij}) \quad (15)$$

where x_{ij} denotes the gain or loss of alternative A_i under attribute C_j, $v(x_{ij})$ is the value function, and $\eta(\omega_j)$ is the weighting function of attribute weight ω_j.

The value function is used to characterize the decision maker's subjective perception of gains and losses, and is defined as:

$$v(x)=\begin{cases}x^{\alpha}, & x\geq 0\\ -\gamma(-x)^{\beta}, & x<0\end{cases} \quad (16)$$

where $x\geq 0$ and $x<0$ represent gains and losses, respectively; α and β are the risk attitude parameters for gains and losses; and γ is the loss aversion coefficient. The weighting function reflects the nonlinear transformation from objective weights to subjective decision weights, and can be written as:

$$\eta(\omega)=\frac{\omega^{\delta}}{\left[\omega^{\delta}+(1-\omega)^{\delta}\right]^{1/\delta}} \quad (17)$$

where ω denotes the objective weight and δ is the parameter describing the sensitivity of weight perception.

3.2 Decision Framework of the Proposed Approach

The decision-making process for evaluating the service quality of IMEC institutions consists of the following five systematic steps:

Step 1: Construction of the initial TIFN decision matrix and normalization

Suppose there are m decision makers $\{DM_1,DM_2,\ldots,DM_m\}$ evaluating p alternatives $\{A_1,A_2,\ldots,A_p\}$ under n attributes $\{C_1,C_2,\ldots,C_n\}$. The evaluation information provided by DM_k is represented as a TIFN matrix $\widetilde{X}^k=\left[\widetilde{A}_{ij}^{k}\right]_{p\times n}$. To eliminate the influence of different dimensions, for benefit attributes, the original values are retained; for cost attributes, the TIFN is transformed using the negation operator: $\widetilde{A}^c=\langle(1-c,1-b,1-a);v,\mu\rangle$.

Step 2: Transformation to connection degree and aggregation of group opinions

Utilizing the bidirectional projection and mapping formulas (Eq. 3 and 4), the normalized TIFNs are transformed into individual connection degree matrices $\Theta^k=\left[\theta_{ij}^{k}\right]_{p\times n}$, where $\theta_{ij}^{k}=a_{ij}^{k}+b_{ij}^{k}\tau+c_{ij}^{k}\varepsilon$. Then, the CDWA operator (Eq. 5) is applied to aggregate individual opinions based on decision makers' weights λ_k. By setting τ=1 and ε=-1, the collective connection degree is quantified into a crisp real-number decision matrix $X=\left[x_{ij}\right]_{p\times n}$.

Step 3: Identification of reference points and calculation of prospect value matrices

Based on the crisp matrix X, the Positive Ideal Solution (PIS, x_j^{+}) and Negative Ideal Solution

(NIS, x_j^-) are defined as reference points. The gain or loss d_{ij} is the distance between x_{ij} and the reference point. According to the CPT value function (Eq. 6), the positive prospect value matrix $V^+=\left[v\left(d_{ij}^+\right)\right]$ and negative prospect value matrix $V^-=\left[v\left(d_{ij}^-\right)\right]$ are constructed.

Step 4: Calculation of decision weights based on known attribute weights

Given the objective attribute weights ω_j, the probability weighting function of CPT (Eq. 8) is employed to calculate the subjective decision weights. This process produces the adjusted positive weights $\eta^+\left(\omega_j\right)$ and negative weights $\eta^-\left(\omega_j\right)$, reflecting the decision makers' non-linear sensitivity to the importance of different attributes.

Step 5: Computation of overall prospect values and ranking of alternatives

Finally, the overall prospect value P_i for each alternative A_i is calculated by integrating the prospect value matrices and the decision weights. All alternatives are ranked according to their overall prospect values P_i in descending order. The alternative with the highest P_i is identified as the optimal choice.

4. Numerical Results

4.1 Problem Description

To demonstrate the feasibility and effectiveness of the proposed decision-making approach, this section presents a numerical case focused on evaluating the service quality of three candidate IMEC institutions, denoted as $\{A_1,A_2,A_3\}$. A panel of three experts specializing in gerontology, nursing, and hospital management was invited to serve as decision makers $\{DM_1,DM_2,DM_3\}$. Based on their professional expertise and the administrative consensus, the weight vector for these decision makers is pre-defined as $\lambda=(0.4,0.3,0.3)^T$. The evaluation is conducted across five core benefit-type attributes identified in Section 2.1: Life Care (C_1), Cultural and Recreational Service (C_2), Medical Nursing Service (C_3), Rehabilitation and Health Care Service (C_4), and Spiritual Comfort Service (C_5), with their corresponding objective weights assigned as $\omega=(0.20,0.15,0.30,0.20,0.15)^T$.

4.2 Decision-Making Process

The decision-making process for the service quality evaluation is executed following the systematic steps outlined in Section 3.2.

4.2.1 Normalization of the initial TIFN decision matrix

Table 2. Initial TIFN Evaluation Decision Matrix

DMs	A_i	C_1	C_2	C_3	C_4	C_5
D_1	A_1	⟨(0.4,0.6,0.8);0.7,0.2⟩	⟨(0.5,0.7,0.8);0.6,0.2⟩	⟨(0.5,0.6,0.8);0.8,0.1⟩	⟨(0.4,0.5,0.7);0.7,0.2⟩	⟨(0.6,0.7,0.9);0.7,0.2⟩
	A_2	⟨(0.6,0.8,0.9);0.8,0.1⟩	⟨(0.6,0.7,0.9);0.8,0.1⟩	⟨(0.7,0.8,0.9);0.8,0.1⟩	⟨(0.7,0.8,0.9);0.9,0.1⟩	⟨(0.5,0.6,0.8);0.7,0.2⟩
	A_3	⟨(0.3,0.4,0.6);0.6,0.3⟩	⟨(0.4,0.5,0.7);0.7,0.2⟩	⟨(0.4,0.5,0.6);0.6,0.2⟩	⟨(0.3,0.4,0.6);0.6,0.3⟩	⟨(0.4,0.6,0.8);0.8,0.1⟩
D_2	A_1	⟨(0.5,0.7,0.8);0.6,0.2⟩	⟨(0.4,0.6,0.7);0.7,0.2⟩	⟨(0.6,0.7,0.8);0.7,0.2⟩	⟨(0.5,0.6,0.8);0.8,0.1⟩	⟨(0.5,0.6,0.7);0.6,0.3⟩
	A_2	⟨(0.7,0.8,0.9);0.7,0.2⟩	⟨(0.5,0.7,0.8);0.7,0.2⟩	⟨(0.8,0.8,0.9);0.8,0.1⟩	⟨(0.6,0.8,0.9);0.7,0.2⟩	⟨(0.7,0.8,0.9);0.8,0.1⟩
	A_3	⟨(0.4,0.5,0.7);0.7,0.2⟩	⟨(0.6,0.7,0.8);0.6,0.3⟩	⟨(0.5,0.6,0.7);0.6,0.3⟩	⟨(0.4,0.5,0.6);0.7,0.2⟩	⟨(0.3,0.5,0.6);0.6,0.3⟩
D_3	A_1	⟨(0.4,0.5,0.7);0.8,0.1⟩	⟨(0.6,0.7,0.8);0.7,0.2⟩	⟨(0.5,0.7,0.9);0.7,0.2⟩	⟨(0.4,0.6,0.7);0.6,0.3⟩	⟨(0.6,0.8,0.9);0.8,0.1⟩
	A_2	⟨(0.6,0.7,0.8);0.8,0.1⟩	⟨(0.7,0.8,0.9);0.7,0.2⟩	⟨(0.7,0.9,0.9);0.9,0.1⟩	⟨(0.7,0.8,0.9);0.8,0.1⟩	⟨(0.6,0.7,0.8);0.7,0.2⟩
	A_3	⟨(0.5,0.6,0.8);0.6,0.2⟩	⟨(0.4,0.5,0.6);0.7,0.2⟩	⟨(0.3,0.5,0.7);0.6,0.2⟩	⟨(0.5,0.6,0.7);0.6,0.3⟩	⟨(0.4,0.5,0.7);0.7,0.2⟩

The evaluation process begins with the collection of linguistic judgments from the three decision makers, which are quantified into TIFNs to form the initial decision matrices. As established in the problem description, there are m=3 decision makers evaluating p=3 candidate institutions under n=5 attributes. The initial evaluation information provided by each DM_k is represented as a TIFN matrix $\widetilde{X}^k=\left[\bar{A}_{ij}^k\right]_{3\times5}$, where each element $\bar{A}_{ij}^k=\langle\left(a_{ij}^k,b_{ij}^k,c_{ij}^k\right);\mu_{ij}^k,v_{ij}^k\rangle$ represents the performance of institution A_i relative to attribute C_j.

To eliminate the influence of different physical dimensions and ensure comparability, the decision matrices must be normalized. According to the attribute definitions in Section 2.1, all five criteria (C_1 to C_5) are identified as benefit-type attributes. In accordance with the normalization rule for TIFNs, for benefit-type attributes, the original evaluation values are retained. Therefore, the normalized decision matrices $\widetilde{R}^k$ are identical to the initial matrices $\widetilde{X}^k$. The comprehensive initial evaluation data integrated for all three decision makers is presented in Table 2.

4.2.2 Transformation to connection degree and aggregation of group opinions

In this step, the bidirectional projection and mapping formulas (Eq. 3 and 4) are applied to transform the normalized TIFNs into individual connection degree matrices $\Theta^k=[\theta_{ij}^k]_{3\times5}$. Each element of the matrix is expressed in the form of $\theta_{ij}^k=a_{ij}^k+b_{ij}^k\tau+c_{ij}^k\varepsilon$, representing the identity, uncertainty, and opposition degrees of the evaluation, respectively. The specific connection degree values provided by the three decision makers for each alternative across the five attributes are presented in Table 3.

Table 3. Individual Connection Degree Matrices for Decision Makers

DMs	Ai	C1	C2	C3	C4	C5
D1	A1	0.215 + 0.519τ + 0.266ε	0.195 + 0.527τ + 0.278ε	0.249 + 0.506τ + 0.245ε	0.139 + 0.492τ + 0.369ε	0.318 + 0.517τ + 0.165ε
	A2	0.516 + 0.451τ + 0.033ε	0.435 + 0.492τ + 0.073ε	0.417 + 0.471τ + 0.111ε	0.595 + 0.405τ + 0.000ε	0.219 + 0.524τ + 0.257ε
	A3	0.000 + 0.429τ + 0.571ε	0.113 + 0.509τ + 0.378ε	0.050 + 0.429τ + 0.522ε	0.000 + 0.405τ + 0.595ε	0.279 + 0.523τ + 0.199ε
D2	A1	0.223 + 0.519τ + 0.258ε	0.144 + 0.518τ + 0.338ε	0.226 + 0.505τ + 0.269ε	0.292 + 0.508τ + 0.200ε	0.107 + 0.499τ + 0.393ε
	A2	0.402 + 0.492τ + 0.106ε	0.239 + 0.529τ + 0.232ε	0.458 + 0.457τ + 0.085ε	0.335 + 0.501τ + 0.164ε	0.558 + 0.442τ + 0.000ε
	A3	0.149 + 0.507τ + 0.344ε	0.173 + 0.524τ + 0.303ε	0.092 + 0.459τ + 0.449ε	0.105 + 0.477τ + 0.418ε	0.000 + 0.442τ + 0.558ε
D3	A1	0.214 + 0.518τ + 0.268ε	0.266 + 0.528τ + 0.206ε	0.240 + 0.506τ + 0.254ε	0.102 + 0.476τ + 0.422ε	0.504 + 0.462τ + 0.034ε
	A2	0.395 + 0.494τ + 0.111ε	0.380 + 0.508τ + 0.112ε	0.551 + 0.416τ + 0.033ε	0.501 + 0.446τ + 0.053ε	0.276 + 0.523τ + 0.201ε
	A3	0.197 + 0.516τ + 0.287ε	0.073 + 0.492τ + 0.435ε	0.066 + 0.446τ + 0.488ε	0.119 + 0.484τ + 0.397ε	0.129 + 0.508τ + 0.363ε

Subsequently, the CDWA operator (Eq. 5) is utilized to aggregate these individual opinions into a collective connection degree matrix based on the expert weight vector $\lambda=(0.4,0.3,0.3)^T$. Following the parameter settings of $\tau=1$ and $\varepsilon=-1$, the integrated collective connection degree for each institutional attribute is quantified into a crisp real-number decision matrix $X=[x_{ij}]_{3\times5}$. This matrix, shown in Table 4, serves as the fundamental input for the behavioral analysis using CPT.

Table 4. Crisp Real-Number Decision Matrix *X*

Ai	C1	C2	C3	C4	C5
A1	0.472	0.452	0.49	0.332	0.611
A2	0.844	0.736	0.84	0.87	0.674
A3	0.164	0.254	0.02	0.035	0.288

4.2.3 Identification of reference points and calculation of prospect value matrices

Based on the crisp real-number decision matrix X, the Positive Ideal Solution (PIS, x^+) and the Negative Ideal Solution (NIS, x^-) for each service quality attribute are identified as the reference points. The PIS and NIS are determined as follows:

PIS: $x^+=[0.844,0.736,0.840,0.870,0.674]$

NIS: $x^-=[0.164,0.254,0.020,0.035,0.288]$

The gain or loss d_{ij} is subsequently calculated as the distance between each evaluation value x_{ij} and the respective reference points. Using the CPT value function (Eq. 6) with the standard parameter settings of $\alpha=\beta=0.88$ and $\gamma=2.25$, the positive prospect value matrix V^+ and the negative prospect value matrix V^- are constructed. The results are presented in Table 5 and Table 6.

Table 5. Positive Prospect Value Matrix V^+

Ai	C1	C2	C3	C4	C5
A1	0.3548	0.2405	0.5146	0.3436	0.3699
A2	0.7122	0.5261	0.8398	0.8533	0.4327
A3	0	0	0	0	0

Table 6. Negative Prospect Value Matrix V^-

Ai	C1	C2	C3	C4	C5
A1	-0.9425	-0.7432	-0.8932	-1.304	-0.1975
A2	0	0	0	0	0
A3	-1.6025	-1.1838	-1.8895	-1.9198	-0.9736

4.2.4 Calculation of decision weights based on known attribute weights

In this step, the objective attribute weights $\omega=(0.20,0.15,0.30,0.20,0.15)^T$ are transformed into subjective decision weights to account for the decision makers' non-linear sensitivity to attribute importance. By employing the CPT probability weighting function (Eq. 8), the adjusted positive and negative decision weight vectors are calculated as follows:

$$\eta^+=(0.202,0.175,0.246,0.202,0.175)^T \quad (18)$$

$$\eta^-=(0.202,0.170,0.257,0.202,0.170)^T \quad (19)$$

These vectors reflect the psychological weight assigned to each attribute in the gain and loss domains, respectively, providing the basis for the subsequent prospect value integration.

4.2.5 Computation of overall prospect values and ranking of alternatives

The final stage involves integrating the prospect value matrices with their corresponding subjective decision weight vectors. The overall prospect value P_i for each institution is calculated using the following formula: $P_i=\sum_{j=1}^{n} v\left(d_{ij}^{+}\right)\eta_j^{+}+\sum_{j=1}^{n} v\left(d_{ij}^{-}\right)\eta_j^{-}$. Based on the evaluation data and weights, the overall prospect values and the final priority ranking of the three candidate institutions are summarized in Table 7.

Table 7. Overall Prospect Values and Final Ranking

Ai	Pi	Ranking
A2	0.6906	1
A1	-0.4688	2
A3	-1.5639	3

The results indicate that the three institutions are ranked as $A_2 \succ A_1 \succ A_3$. Institution A_2 achieves the highest overall prospect value (P_2=0.6906), identifying it as the optimal institution among the candidates. This superior result is primarily attributed to its outstanding performance in Medical Nursing Service (C_3) and Rehabilitation and Health Care Service (C_4), which are the most critical dimensions in the evaluation of IMEC service quality.

5. Result Analysis and Managerial Insights

5.1 Result Analysis

The evaluation results, calculated through the integration of TIFNs and CPT, indicate that the three candidate institutions are ranked as $A_2 \succ A_1 \succ A_3$. Institution A_2 achieved the highest overall prospect value, identifying it as the optimal service provider.

A deeper analysis of the crisp decision matrix X and the attributes reveals that A_2's dominance is primarily rooted in its outstanding performance in Medical Nursing Service (C_3) and Rehabilitation and Health Care Service (C_4), where it scored 0.84 and 0.87 respectively. Given that these two criteria carry the highest objective weights (ω_3=0.30,ω_4=0.20), A_2 's strength in medical-related dimensions effectively offset its slightly lower performance in spiritual comfort compared to A_1. Conversely, A_3 ranked lowest due to significant performance gaps across all core attributes, particularly in rehabilitation services, resulting in a substantial negative prospect value.

5.2 Managerial Insights

Based on the implementation of the proposed decision-making framework and the empirical findings, the following managerial insights are provided for the improvement of IMEC service quality:

Strengthen the "Medical" Component in IMEC: The study underscores that medical nursing and rehabilitation are the most critical dimensions in the evaluation system. Institutions should prioritize the allocation of resources toward professional medical equipment and qualified nursing staff to meet the essential health demands of elderly residents.

Account for Decision-Makers' Psychological Factors: The application of CPT shows that experts do not always act as purely "rational" agents; they are sensitive to risks and losses relative to reference points. Managers should identify industry benchmarks and strive to exceed these thresholds to ensure positive psychological perceptions of their service quality.

Optimize Comprehensive Service Delivery: While medical care is a priority, high-quality institutions must maintain a balanced performance. As seen in the case of A_2 , achieving the top rank requires not only excellence in core medical attributes but also maintaining competitive standards in life care and cultural services to avoid being penalized by loss aversion in the decision-making process.

6. Conclusions

This study addressed the critical issue of service quality evaluation in IMEC institutions by proposing a comprehensive MCGDM framework. By integrating TIFN with CPT, the developed model successfully captured the inherent uncertainty of linguistic evaluations and the psychological risk preferences of decision-makers.

The main conclusions of this research are summarized as follows:

Methodological Effectiveness: The proposed approach provides a robust mathematical tool for handling complex, fuzzy information in elderly care assessments. The use of bidirectional projection and connection degree transformation ensures that the final rankings are both scientifically grounded and consistent with human cognitive patterns.

Identification of Key Quality Drivers: Through the empirical analysis of three institutions, A_2

was identified as the optimal alternative. The results underscore that Medical Nursing Service and Rehabilitation and Health Care Service are the most influential factors in determining high-level service quality in the current IMEC landscape.

Practical Implications: The findings suggest that for IMEC institutions to enhance their competitiveness, they must prioritize the organic integration of professional medical resources while maintaining high standards in daily life care and spiritual support.

In summary, this research offers a valuable decision-support tool for government agencies, elderly care investors, and facility managers to scientifically evaluate performance and optimize resource allocation, ultimately contributing to the development of a high-quality "Active Aging" service system.

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