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An Intuitionistic Fuzzy Hybrid Weighting and Ranking Approach for R&D-oriented PPP Project Selection with Interdependent Criteria

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Abstract *–Public-Private Partnership (PPP) projects have become an effective mechanism for delivering large-scale infrastructure and development initiatives by integrating public-sector objectives with private-sector resources, expertise, and risk-sharing capabilities. In particular, R&D-oriented PPP projects play a significant role in supporting urban development through innovation-driven investments, improved service quality, and more efficient allocation of financial, human, and technical resources. However, selecting the most appropriate PPP project is a complex multi-criteria decision-making (MCDM) problem, especially when evaluation criteria are interdependent, and decision information is subject to uncertainty. To address this issue, this study proposes an intuitionistic fuzzy hybrid weighting and ranking approach for R&D-oriented PPP project selection with interdependent criteria. This study also proposes an integrated decision-support framework for the selection of R&D-oriented PPP projects. The framework systematically combines well-established intuitionistic fuzzy methods, IF-ANP and IF-DEMATEL for criteria weighting, IF-CS for decision-maker (DM) weighting, and an intuitionistic fuzzy ranking procedure, to address uncertainty and interdependencies among criteria in a realistic case study. To validate the applicability of the proposed approach, a case study in urban development is conducted. The results show that the proposed model provides a practical and robust decision-support tool for project managers by improving the handling of uncertainty, interdependence, and group decision-making. In addition, a comparative analysis with an existing method from the literature confirms the efficiency and robustness of the proposed framework.*

Keywords– *R&D-oriented PPP projects; Multi-criteria decision-making; Intuitionistic fuzzy sets; ANP-DEMATEL; Interdependent criteria.*

I. INTRODUCTION

Economic development is a critical global challenge, requiring sustained investment in foundational infrastructure to drive employment, production, and long-term success (Abad-Segura & González-Zamar, 2021; Barzegari & Mousavi, 2026). While the timely and cost-effective execution of such projects serves as a key indicator of economic vitality (Ren et al., 2021), the construction and infrastructure sectors frequently face hurdles related to delays and budget overruns, prompting governments to move away from direct participation (Davoudabadi et al., 2019; Gitinavard et al., 2019; Gitinavard et al., 2020; Hamzeh et al., 2020). Consequently, partnering with the private sector has emerged as a

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recommended strategy to secure the necessary financial, technical, and human resources for infrastructure delivery (Gitinavard et al., 2014; Wen, 2021). This shift is particularly urgent given the rapid population growth and the resulting need for sustainable development (Essounga & Njiei, 2021), which necessitates the expansion of essential urban systems, such as transportation networks, roads, and public transit, to meet the rising demands of modern societies (Kashef & El-Shafie, 2020; Yuan et al., 2020).

Within this context, Public-Private Partnership (PPP) projects have emerged as a key methodology, where the private sector assumes responsibility for capital, human resources, and equipment as investors (Askarianzadeh et al., 2024; Tang et al., 2010). Historically, governments led these large-scale infrastructure endeavors; however, these projects demand substantial resources and carry inherent risks that can lead to project failure and significant societal losses (Ebrahimnejad et al., 2017; Gitinavard et al., 2017; Tavana et al., 2021). To mitigate these risks, governments are increasingly collaborating with the private sector (Borujeni & Gitinavard, 2017; Kim, 2022).

Crucially, modern urban infrastructure is transitioning from traditional asset building toward high-tech, smart, and sustainable systems. This evolution has fostered the emergence of R&D-oriented PPP projects, which integrate research and development, technological innovation, and advanced engineering into public services (Ghaderi et al., 2020; Kryukov et al., 2016; Mousavi & Gitinavard, 2019). Unlike conventional PPPs, R&D-oriented PPPs demand a complex evaluation of technological feasibility, innovation capacity, and long-term research benefits along with standard financial and operational metrics. Under these long-term contracts, factors such as technical infrastructure and labor laws significantly influence the attraction of private investment and contribute to economic growth (Kilinkarova et al., 2020), ensuring a clear sharing of risks, responsibilities, and benefits (Dorfeshan & Abdzadeh, 2026; Gitinavard et al., 2014).

Research into PPP projects spans various scales and contexts. Kim & Choi (2018) studied the negotiation and finalization of PPP contracts using South Korea's Songdo New Town project as a case study. Kavishe et al. (2019) evaluated the challenges and outcomes of PPP construction projects in developing countries such as Tanzania, highlighting cost-effectiveness and affordable housing. Xiong et al. (2020) explored lessons from China, viewing the PPP approach as a governmental strategy for sustainable urban development. Suriyanti et al. (2020) examined the benefits of private sector involvement in manufacturing under PPP conditions, while Rahmah & Zaidun (2019) analyzed the impact of PPPs in Indonesian construction. Extending the concept, Seddighi et al. (2021) examined the use of a public-private-people partnership (4P) model during the COVID-19 pandemic to manage public health operations.

More recent research has focused on analytical, risk-assessment, and optimization models in infrastructure systems. Ghasemi et al. (2023) proposed a mixed-integer linear model for optimizing cost, time, and quality under interval incomplete information. Kukah et al. (2023) extended a fuzzy synthetic evaluation methodology to assess risk factors for PPP power projects in Ghana. In Iran, Jokar et al. (2023) developed a risk allocation model for PPP freeway projects, integrating AHP, TOPSIS, and DEMATEL methodologies. Furthermore, Kukah et al. (2024) defined a fuzzy quantitative model based on risk allocation principles. Du et al. (2025) presented a hybrid fuzzy multi-criteria framework utilizing Geographic Information Systems to support site selection decisions for wind-photovoltaic hydrogen co-production facilities. Moreover, Awang et al. (2026) proposed an Intuitionistic Trapezoidal Fuzzy DEMATEL (ITF-DEMATEL) model to analyze and evaluate the interrelated factors influencing the adoption of Green Manufacturing (GM). Choudhary et al. (2024) applied intuitionistic fuzzy DEMATEL to identify and analyze the cause–effect relationships and relative importance of critical success factors in humanitarian supply chains.

Despite these advancements, evaluating and selecting R&D-oriented PPP projects remains a significant challenge due to two main issues. First, the evaluation criteria, spanning financial feasibility, technological innovation, social impact, and environmental sustainability, are highly interdependent in real-world scenarios. Second, expert judgments are often characterized by vagueness and hesitation. While Multi-Criteria Decision-Making (MCDM) offers a viable framework, traditional methods fail to capture the complex interdependencies among criteria under high levels of uncertainty.

Although recent advancements have been made in PPP project evaluation, selecting R&D-oriented PPP projects remains a challenging task for which conventional methods in the literature often prove inadequate. This difficulty arises from two closely related characteristics of the problem. First, the evaluation criteria, covering financial feasibility, technological innovation, social impact, and environmental sustainability, are inherently interdependent in real-world settings. For example, changes in technological feasibility may directly affect cost as well as long-term research benefits. Second, the information required for such assessments is often incomplete and imprecise, meaning expert judgments are typically expressed with vagueness and hesitation. Although Multi-Criteria Decision-Making (MCDM) offers a natural framework for this class of problems, most existing methods are not designed to handle these two features simultaneously. Conventional techniques such as AHP and TOPSIS generally assume criteria independence, which may lead to biased weights and unreliable rankings. Meanwhile, methods that consider interdependence, such as ANP or DEMATEL, are often applied separately and do not explicitly represent the incompleteness and hesitation inherent in expert judgments. In PPP settings, where decisions involve substantial capital commitments and long-term consequences, selecting an unsuitable project can be costly and difficult to reverse. Therefore, a framework that jointly models criteria interdependence and judgment uncertainty is not merely a methodological improvement but a practical necessity. The present study is motivated by exactly this need. The main contributions of this paper are as follows:

- In contrast to approaches that treat evaluation criteria as independent, a combined IF-ANP–IF-DEMATEL weighting framework is introduced to capture both feedback loops and mutual influences among the criteria of R&D-oriented PPP projects.
- The Compromise Solution (CS) method, originally developed for group decision problems with crisp data, is extended to an intuitionistic fuzzy environment to derive DMs' weights systematically.
- An intuitionistic fuzzy ranking method is developed to prioritize project alternatives under uncertainty while preserving the information embedded in experts' hesitation.
- A real-world case study in urban development is used to validate the applicability, efficiency, and robustness of the proposed model.

The rest of the paper is organized as follows: Section 2 presents the preliminaries of intuitionistic fuzzy sets and the related concepts used in this study. Section 3 introduces the proposed intuitionistic fuzzy hybrid weighting and ranking framework, integrating IF-DEMATEL, IF-ANP, and IF-CS to address interdependent criteria and uncertainty in expert judgments. Section 4 presents the real-world case study on R&D-oriented PPP project selection in urban development. Section 5 provides the sensitivity and comparative analyses. Finally, Section 6 concludes the paper and suggests directions for future research.

II. PROPOSED APPROACH

This section examines the proposed decision-making approach based on computing the criteria weights, DM's weights, and the rank of the conflicting alternatives. The proposed methodology is presented in a step-by-step format to facilitate replication. Specifically, the procedure includes the construction of the decision matrix, the derivation of criteria weights using IF-ANP and IF-DEMATEL, the determination of DMs' weights using IF-CS, and the ranking of alternatives using the proposed intuitionistic fuzzy ranking method. The corresponding computational steps and equations are provided to ensure transparency and reproducibility.

The experts' pairwise judgments are expressed as intuitionistic fuzzy values (IFVs), $a_{ij} = (\mu_{ij}, \nu_{ij})$, where the hesitation degree is given by $\pi_{ij} = 1 - \mu_{ij} - \nu_{ij}$. Since the classical DEMATEL procedure requires a real-valued direct-relation matrix for subsequent normalization and causal analysis, the IFVs are transformed into scalar scores using a standard intuitionistic fuzzy score function. Accordingly, the values reported in the case study section correspond to these score-function outputs rather than raw IFVs. This transformation is applied only for the DEMATEL computational stage and does not alter the original intuitionistic fuzzy elicitation process. For this purpose, the following steps are described.

Step 1. Create the intuitionistic fuzzy decision-making matrix (P) based on the expert's judgments. To initiate the decision-making process, experts are provided with the evaluation criteria and project alternatives. They are asked to perform pairwise comparisons or direct assessments based on intuitionistic fuzzy sets, characterized by membership (μ) and non-membership (v) degrees. The collected judgments are aggregated to construct the intuitionistic fuzzy decision matrix P, where $p_{ij} = [\mu_{ij}, v_{ij}]$ represents the evaluation of alternative A_i regarding criterion C_j.

$$P = \begin{array}{c} \\ A_1 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & \dots & C_j \end{array} \\ \begin{bmatrix} \{[\mu_{11}^1, v_{11}^1], [\mu_{11}^2, v_{11}^2], \dots, [\mu_{11}^k, v_{11}^k]\} & \cdots & \{[\mu_{1n}^1, v_{1n}^1], [\mu_{1n}^2, v_{1n}^2], \dots, [\mu_{1n}^k, v_{1n}^k]\} \\ \vdots & \ddots & \vdots \\ \{[\mu_{m1}^1, v_{m1}^1], [\mu_{m1}^2, v_{m1}^2], \dots, [\mu_{m1}^k, v_{m1}^k]\} & \cdots & \{[\mu_{mn}^1, v_{mn}^1], [\mu_{mn}^2, v_{mn}^2], \dots, [\mu_{mn}^k, v_{mn}^k]\} \end{bmatrix}_{m\times n} \end{array} \quad \forall k \tag{1}$$

Step 2. Obtain the criteria weights based on the Intuitionistic Fuzzy Analytic Network Process (IF-ANP) method. Following the construction of the decision matrix, the relative importance of the criteria is determined. Since criteria are interdependent, the IF-ANP is employed to model the network of influences. The weighting procedure is structured as follows:

Step 2.1. Construct the super matrix. Based on expert opinions regarding the interdependencies among criteria, an intuitionistic fuzzy influence matrix R is constructed for each DM k. This matrix maps the direct influences between any two criteria $C_i$and C_j.

$$R = \begin{array}{c} \\ C_1 \\ \vdots \\ C_j \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & \dots & C_j \end{array} \\ \begin{bmatrix} r_{11}^k & \cdots & r_{1n}^k \\ \vdots & \ddots & \vdots \\ r_{n1}^k & \cdots & r_{nn}^k \end{bmatrix}_{n\times n} \end{array} \quad \forall k \tag{2}$$

Step 2.2. Determine the local priority vector for each pairwise comparison matrix. For each DM *k*, the eigenvector associated with the pairwise comparison matrix is obtained using Eq. (18). This vector represents the relative priority of the criteria within the corresponding comparison matrix.

$$O = I_{enb} w \tag{3}$$

In Eq. (18), O denotes the pairwise comparison matrix, I_{enb} represents the corresponding identity matrix, and w is the local priority vector to be estimated.

Step 2.3. Normalize the local priority vectors. The local priority values obtained in Step 2.2 are normalized using Eqs. (19) and (20) so that the elements in each column sum to one. The normalized vectors are then used to construct the weighted supermatrix.

$$N_i = \begin{bmatrix} n_{11}^k \\ n_{21}^k \\ \vdots \\ n_{n1}^k \end{bmatrix}_{n\times 1} \quad \forall k \tag{4}$$

$$n_{ij}^k = \frac{r_{ij}^k}{\sum_{i=1}^m r_{ij}^k} \quad \forall k \tag{5}$$

In Eq. (19), N_i denotes the normalized priority vector corresponding to criterion C_i, while n_{ij}^k in Eq. (20) denotes the normalized influence value of criterion C_i on criterion C_j for DM k.

Step 2.4. Compute the IF-ANP-based criteria weights. The normalized local priority vectors are aggregated to construct matrix K, as given in Eq. (21). Subsequently, the global weight of each criterion is calculated using Eq. (22). The resulting vector $w = [w_1, w_2, ..., w_n]^T$ represents the IF-ANP-based weights of the criteria and is used as an input to the combined weighting procedure in Step 4.

$$K = [n_{ij}^k] \qquad \forall i,j \tag{6}$$

$$GW_j = \frac{\sum_{j=1}^{n} K_{ij}}{n} w = [1 \times w]_{n\times 1} \qquad \forall i \tag{7}$$

A higher value of GW_j indicates a greater relative importance of criterion C_j within the network of interdependent criteria.

Step 3. Determine the criteria weights using the IF-DEMATEL method. This phase measures the causal relationships and strength of influence among the evaluation criteria. The detailed procedural steps of this phase are described below:

Step 3.1. Construct the individual intuitionistic fuzzy direct-influence matrix (Q_k) for each DM $k(k = 1,2,\ldots,K)$. Each DM evaluates the direct influence of criterion $C_i$on criterion $C_j$using the predefined linguistic terms, which are then converted into intuitionistic fuzzy numbers $[\mu_{ij}^k, v_{ij}^k]$:

$$Q_k = \begin{array}{c c} & \begin{array}{ccc} C_1 & \ldots & C_j \end{array} \\ \begin{array}{c} C_1 \\ \vdots \\ C_j \end{array} & \begin{bmatrix} [\mu_{11}^k, v_{11}^k] & \cdots & [\mu_{1n}^k, v_{1n}^k] \\ \vdots & \ddots & \vdots \\ [\mu_{n1}^k, v_{n1}^k] & \cdots & [\mu_{nn}^k, v_{nn}^k] \end{bmatrix}_{n\times n} \end{array} \qquad \forall k \tag{8}$$

Step 3.2. Aggregate the individual judgments to construct the group direct-influence matrix ($Q = [I_{ij}]_{n\times n}$). The individual intuitionistic fuzzy direct-influence matrices are aggregated into a single group direct-influence matrix. After aggregating via the IFWA operator and defuzzifying the result, we obtain the crisp values I_{ij}. The individual intuitionistic fuzzy assessments were aggregated by the IFWA operator and then defuzzified to obtain the crisp direct-relation values I_{ij}. The normalization was subsequently applied to the resulting crisp direct-relation matrix, as in the standard DEMATEL procedure.

$$I_{ij} = score\left(\bigoplus_{k=1}^{K}\left(\frac{1}{k}[\mu_{ij}, v_{ij}]\right)\right) = \frac{1}{R}\sum_{r=1}^{R}\left(\frac{1}{l}\sum_{\lambda=1}^{l}\left[1 - \frac{\prod_{k=1}^{K}\left(1-[\mu_{ij}, v_{ij}]^{\sigma(\lambda)}\right)^{\frac{1}{k}}}{2}\right]\right) \tag{9}$$

The aggregated direct-influence matrix Q is represented as:

$$Q = \begin{array}{c c} & \begin{array}{ccc} C_1 & \ldots & C_j \end{array} \\ \begin{array}{c} C_1 \\ \vdots \\ C_j \end{array} & \begin{bmatrix} 0 & \cdots & I_{1n} \\ \vdots & \ddots & \vdots \\ I_{n1} & \cdots & 0 \end{bmatrix}_{n\times n} \end{array} \tag{10}$$

Step 3.3. Normalize the aggregated direct-influence matrix ($Q^N = [L_{ij}^N]_{n\times n}$). The normalization ensures that the values are within the range $[0, 1]$:

$$
{Q_{\acute{j}j}}^{N} = \begin{array}{c c} & \begin{array}{ccc} C_1 & \dots & C_j \end{array} \\ \begin{array}{c} C_1 \\ \vdots \\ C_j \end{array} & \begin{bmatrix} 0 & \cdots & L_{1n}^{N} \\ \vdots & \ddots & \vdots \\ L_{n1}^{N} & \cdots & 0 \end{bmatrix}_{n\times n} \end{array} \tag{11}
$$

$$
L_{\acute{j}j}^{N} = \frac{I_{\acute{j}j}}{\max\limits_{0\leq i\leq n}\left\{\sum_{j=1}^{n} I_{ij}\right\}} \qquad \forall \acute{j}, j \tag{12}
$$

Step 3.4. Derive the total-influence matrix ($P = \left[p_{ij}\right]_{n\times n}$). The total-influence matrix, incorporating both direct and indirect relationships, is calculated as:

$$
P_{\acute{j}j} = \begin{array}{c c} & \begin{array}{ccc} C_1 & \dots & C_j \end{array} \\ \begin{array}{c} C_1 \\ \vdots \\ C_j \end{array} & \begin{bmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{n1} & \cdots & p_{nn} \end{bmatrix}_{n\times n} \end{array} \tag{13}
$$

$$
P_{\acute{j}j} = {Q_{\acute{j}j}}^{N} \left|\left(I - {Q_{\acute{j}j}}^{N}\right)^{-1}\right| \tag{14}
$$

where I denotes the $n \times n$ identity matrix.

Step 3.5. Compute the final criteria weights (w_j). The final DEMATEL-based weight of each criterion C_j is determined by the prominence of each criterion:

$$
w_j = \frac{\nabla_j + \nabla_j \times P_{\acute{j}j}}{\sum_{j=1}^{n}\left(\nabla_j + \nabla_j \times P_{\acute{j}j}\right)} \qquad \forall\, k, p, j, \acute{j} \tag{15}
$$

where $\left[\nabla_j\right]_{1\times n}$ is $1 \times n$ matrix and $\left[P_{\acute{j}j}\right]_{n\times n}$ is $n \times n$ matrix.

Step 4. Derive the final criteria weights based on the IF-ANP network structured by IF-DEMATEL. The IF-DEMATEL analysis is employed to identify the causal relationships and influence structure among the criteria. The resulting cause–effect structure is then used to define the dependence relationships and feedback links required for constructing the IF-ANP network. Accordingly, IF-DEMATEL is not used as an independent source of numerical weights to be multiplied by the ANP weights. After constructing the IF-ANP supermatrix according to the interdependencies identified through IF-DEMATEL, the weighted supermatrix is raised to limiting powers. The resulting limit supermatrix provides the global priority weights of the criteria. Therefore, the final weight of criterion C_j, denoted by τ_j^{w}, is directly obtained from its corresponding global priority in the limit supermatrix:

$$
\tau_j^{w} = \frac{w_j GW_j}{\sum_{j=1}^{m}\left(w_j GW_j\right)} \qquad \acute{r} \subseteq \mathrm{j} \tag{16}
$$

This sequential integration preserves the complementary roles of the two methods. Specifically, IF-DEMATEL reveals the causal influence structure among criteria, whereas IF-ANP quantifies the final network-based priorities by accounting for the identified interdependencies and feedback effects. Thus, the two methods are integrated structurally rather than through a post hoc multiplicative combination of two normalized weight vectors.

Step 5. Determine the weights of the DMs using the IF-CS approach. This phase calculates the relative importance of the DMs based on the consistency of their intuitionistic fuzzy evaluations with respect to the positive and negative ideal solutions.

Step 5.1. Construct the intuitionistic fuzzy decision matrix for each DM. For each DM $k (k = 1,2, \dots, K)$, the intuitionistic fuzzy decision matrix is formed as follows:

$$NO = \begin{array}{c} \\ A_1 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & \dots & C_j \end{array} \\ \begin{bmatrix} [\mu_{11}^k, v_{11}^k] & \cdots & [\mu_{1n}^k, v_{1n}^k] \\ \vdots & \ddots & \vdots \\ [\mu_{m1}^k, v_{m1}^k] & \cdots & [\mu_{mn}^k, v_{mn}^k] \end{bmatrix}_{m\times n} \end{array} \quad \forall k \tag{17}$$

where m and n denote the numbers of alternatives and criteria, respectively.

Step 5.2. Determine the intuitionistic fuzzy positive and negative ideal solutions. The intuitionistic fuzzy positive ideal solution (IF-PIS) and intuitionistic fuzzy negative ideal solution (IF-NIS) are defined as:

$$NO^+ = \left([\mu_{ij}^+, v_{ij}^+]\right)_{m\times n} = \begin{array}{c} \\ A_1 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & \dots & C_j \end{array} \\ \begin{bmatrix} [\mu_{11}^+, v_{11}^+] & \cdots & [\mu_{1n}^+, v_{1n}^+] \\ \vdots & \ddots & \vdots \\ [\mu_{m1}^+, v_{m1}^+] & \cdots & [\mu_{mn}^+, v_{mn}^+] \end{bmatrix}_{m\times n} \end{array} \tag{18}$$

$$NO^- = \left([\mu_{ij}^-, v_{ij}^-]\right)_{m\times n} = \begin{array}{c} \\ A_1 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & \dots & C_j \end{array} \\ \begin{bmatrix} [\mu_{11}^-, v_{11}^-] & \cdots & [\mu_{1n}^-, v_{1n}^-] \\ \vdots & \ddots & \vdots \\ [\mu_{m1}^-, v_{m1}^-] & \cdots & [\mu_{mn}^-, v_{mn}^-] \end{bmatrix}_{m\times n} \end{array} \tag{19}$$

where the elements of the positive and negative ideal matrices are obtained as follows:

$$\mu_{ij}^+ = \frac{1}{K}\sum_{k=1}^{K} \mu_{ij}^k \tag{20}$$

$$v_{ij}^+ = \frac{1}{K}\sum_{k=1}^{K} v_{ij}^k \tag{21}$$

$$\mu_{ij}^- = \min_k(\mu_{ij}^k) \tag{22}$$

$$v_{ij}^- = \min_k(v_{ij}^k) \tag{23}$$

Step 5.3. Compute the separation measures from the IF-PIS and IF-NIS. The separation measures of each DM from the intuitionistic fuzzy positive and negative ideal solutions are calculated using the Euclidean distance in the $m \times n$ intuitionistic fuzzy decision space:

$$M_k^+ = \sqrt{\tfrac{1}{2n}\textstyle\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\left|\mu_{ij}^k(x_i) - NO_{ij}^+(x_i)\right|^2 + \left|v_{ij}^k(x_i) - NO_{ij}^+(x_i)\right|^2\right)} \quad \forall k \tag{24}$$

$$M_k^- = \sqrt{\frac{1}{2n}\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\left|\mu_{ij}^k(x_i) - NO_{ij}^-(x_i)\right|^2 + \left|v_{ij}^k(x_i) - NO_{ij}^-(x_i)\right|^2\right)} \quad \forall k \tag{25}$$

Step 5.4. Compute the weight of each DM. The weight of each DM is obtained according to the relative closeness coefficient:

$$WD_k = \frac{M_k^-}{(M_k^- + M_k^+)\left(\sum_{k=1}^{K} \frac{M_k^-}{M_k^- + M_k^+}\right)} \qquad \forall k \qquad (26)$$

where WD_k denotes the normalized weight assigned to DM k.

Step 6. Rank the alternatives using the proposed ranking approach. In this step, a new ranking index is developed to prioritize the alternatives by considering both benefit and cost criteria.

Step 6.1. Calculate the aggregated performance of each alternative $i$for the benefit (positive) criteria, denoted by A_i^k, for each DM k: Assuming criteria $j = 1, \dots, t$ are benefit criteria, $A_i^k$is computed as:

$$A_i^k = \left[1 - \prod_{j=1}^{t}\left(1 - \mu_{ij}^k\right), 1 - \prod_{j=1}^{t}\left(1 - v_{ij}^k\right)\right] \qquad \forall k, i \qquad (27)$$

Step 6.2. Calculate the aggregated performance for the cost (negative) criteria, denoted by E_i^k. Assuming criteria $j = t + 1, \dots, n$are cost criteria, E_i^k is computed as:

$$E_i^k = \left[1 - \prod_{j=t+1}^{n}\left(1 - \mu_{ij}^k\right), 1 - \prod_{j=t+1}^{n}\left(1 - v_{ij}^k\right)\right] \qquad \forall k, i \qquad (28)$$

Step 6.3. Identify the smallest performance value among cost criteria for each DM:

$$E_{min}^k = \left[\min_i E_i^k\right] \qquad \forall k \qquad (29)$$

It should be noted that $E_i$and $E_{\min}$are used to determine the relative weights of the DMs, rather than to rank or normalize the alternatives. The value $E_{\min}$serves as a reference value in the IF-CS weighting procedure after evaluating the DMs' consistency with respect to the positive and negative ideal solutions. The alternative ranking is conducted separately using the aggregated intuitionistic fuzzy decision information and the final criteria weights.

Step 6.4. Determine the relative importance (RI_i^k) of each alternative. The IFWG operator is monotone, idempotent, and bounded by the boundaries of the unit interval, making it a theoretically validated aggregation function (Xu & Yager, 2006).

$$RI_i^k = \left[A_i^k + (1 - A_i^k)\left(\frac{1 - \left(\prod_{i=1}^{m}\left(1 - E_i^k\right)\right)^{E_{min}^k}}{1 - \left(\prod_{i=1}^{m}\left(1 - \frac{E_{min}^k}{E_i^k}\right)\right)^{E_i^k}}\right)\right] \qquad \forall k, i \qquad (30)$$

Step 6.5. Aggregate the individual relative importance values into a collective index (RF_i) using the DMs' weights (WD_k):

$$RF_i = \bigcup \widetilde{RF}_1 \in \tilde{h}_{q1}, \dots, \widetilde{RF}_k \in \tilde{h}_{qk} \times \left\{\left[\prod_{k=1}^{K} {RI_i^k}^{WD_k}\right]\right\} \qquad \forall i \qquad (31)$$

Step 6.6. Calculate the utility degree (UT_i) for each alternative to determine the final ranking:

$$UT_i = \left[\frac{RF_i}{\max(RF_i\ )}\right] 100\% \qquad \forall i \tag{32}$$

Step 7. Final ranking. The alternatives are ranked in descending order of their utility degrees (UT_i). The alternative with the highest UT_i value is selected as the best R&D-oriented PPP project.

III. CASE STUDY

This study presents a real-world, expert-based case study in urban development, rather than a hypothetical numerical illustration, to validate the applicability of the proposed model in practical R&D-oriented PPP project selection. A panel of three DMs (DM_1, DM_2, DM_3), comprising senior project managers, financial analysts, and infrastructure experts, was tasked with evaluating the candidate projects using linguistic terms that were represented in Tables I and II. The evaluation was conducted based on ten critical financing and development criteria (C_1, C_2, …, C_{10}), as detailed in Table III. These criteria were compiled from the current practices of the involved organization and further refined through expert consensus using the Delphi method, ensuring that both traditional financial indicators and R&D-oriented factors, such as technological feasibility, innovation capacity, and long-term research benefits, were adequately represented. In this study, three primary R&D-oriented PPP project alternatives were considered:

- A_1: Highway construction with integrated smart transportation technologies,
- A_2: Bridge construction incorporating advanced structural innovation and monitoring systems,
- A_3: Metro development with intelligent urban mobility and research-driven design solutions.

These alternatives reflect the growing trend of embedding research, development, and technological innovation into conventional urban infrastructure projects. Expert judgments were first elicited to ascertain the relative importance of each criterion under uncertainty, capturing the inherent hesitation and vagueness in the DMs' assessments. These judgments were subsequently transformed into Intuitionistic Fuzzy (IF) values to model the uncertainty more realistically. The proposed hybrid IF-ANP and IF-DEMATEL framework was then applied to compute the criteria weights by accounting for their interdependencies, while the IF-CS method was used to determine the weights of the DMs. Finally, the candidate R&D-oriented PPP projects were ranked using the proposed intuitionistic fuzzy ranking approach.

Although the criteria listed in Table III are composed primarily of financial, managerial, and risk-related indicators, they are appropriate for the selection stage of R&D-oriented PPP projects because they represent the necessary preconditions for successful project implementation. In the PPP context, even innovation-intensive projects must demonstrate bankability, risk manageability, institutional compatibility, and delivery feasibility before their R&D potential can be realized. Therefore, the present criterion set is intended to capture the fundamental feasibility dimensions of R&D-oriented PPP projects. Innovation-specific attributes such as technology transfer, intellectual property management, and absorptive capacity are recognized as important and are recommended as extensions for future studies.

Table I. The linguistic variables to appraise the criteria's importance

Linguistic variables	IFVs
Very low (VL)	(0.1,0.1)
Low (L)	(0.2,0.3)
Medium (M)	(0.3,0.5)
High (H)	(0.4,0.6)
Very high (VH)	(0.45,0.55)

Table II. The linguistic variables to rate the alternatives

Linguistic variable	IFVs
Absolutely high (AH)	(0.49,0.5)
Very very high (VVH)	(0.47,0.49)
Very high (VH)	(0.45,0.47)
High (H)	(0.43,0.45)
Medium high (MH)	(0.4,0.43)
Medium (M)	(0.35,0.4)
Medium low (ML)	(0.3,0.35)
Low (L)	(0.2,0.25)
Very low (VL)	(0.15,0.2)
Very very low (VVL)	(0.1,0.1)

Table III. The definition of the criteria

Criteria	Description
C_1	Government support for private sector participation
C_2	Inflation risk and its impact on construction, operation, and long-term project viability
C_3	Risk of delayed government payments and financial obligations
C_4	Adequacy of legal and regulatory familiarity with international PPP frameworks
C_5	Appropriateness of partner selection and contractor qualification
C_6	Risk arising from subjective preferences of senior managers in project decision-making
C_7	Exchange rate fluctuations and their impact on project financing
C_8	Capability to secure banking facilities and financial support
C_9	Availability of equipment, machinery, raw materials, and technological resources
C_{10}	Company working capital and financial liquidity capacity

In addition, the relations among criteria and alternatives are determined in Table IV, which is based on the experts' opinions. The criteria weight judgments based on the DMs' opinions are shown in Table V. Although the illustrative case study employed three DMs and ten main criteria, the proposed framework is inherently scalable. The number of DMs can be increased without any restriction, as the aggregation mechanism (IFWG) supports an arbitrary number of expert judgments. Similarly, the ANP-based structure allows each main criterion to be decomposed into sub-criteria, and the same weighting and ranking procedure applies at every level of the hierarchy. Furthermore, the linguistic scale can be refined (e.g., to seven or nine levels) whenever higher discriminating power is required. These properties ensure that the proposed framework can be directly adapted to real-world R&D-oriented PPP project selection problems involving larger stakeholder groups and more detailed criterion hierarchies. Furthermore, Table VI presents the pairwise comparisons among the criteria.

Table IV. The performance measure of the alternatives with linguistic variables

Criteria	Alternatives	DMs		
		DM_1	DM_2	DM_3
C_1	A_1	L	H	L
	A_2	H	M	VH
	A_3	M	M	H
C_2	A_1	L	VH	H
	A_2	M	L	L
	A_3	H	H	H
C_3	A_1	VH	M	L
	A_2	M	H	VH
	A_3	H	L	H
C_4	A_1	L	H	VH
	A_2	H	M	M
	A_3	M	M	M
C_5	A_1	VH	L	M
	A_2	H	H	L
	A_3	H	M	VH
C_6	A_1	L	L	H
	A_2	H	M	H
	A_3	L	VH	L
C_7	A_1	VH	VH	H
	A_2	H	M	L
	A_3	VH	VH	VH
C_8	A_1	M	L	H
	A_2	M	H	VH
	A_3	L	M	H
C_9	A_1	L	L	M
	A_2	H	H	L
	A_3	L	M	VH
C_{10}	A_1	L	L	H
	A_2	H	M	H
	A_3	VH	VH	L

Table V. The weights of the criteria based on experts' judgments

Criteria	DMs		
	DM_1	DM_2	DM_3
C_1	H	H	VH
C_2	H	M	H
C_3	VVH	VH	H
C_4	VH	AH	VH
C_5	H	AH	VVH
C_6	VH	AH	MH
C_7	VVH	VVH	VH
C_8	MH	H	MH
C_9	VH	VH	AH
C_{10}	MH	AH	AH

Table VI. The pairwise comparison decision matrix

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
DM_1										
C_1	0	H	H	L	VH	H	H	M	VVH	VH
C_2	H	0	ML	M	M	H	H	VVH	M	AH
C_3	H	ML	0	L	M	M	H	H	VVH	VVH
C_4	L	M	L	0	VH	VH	L	VH	VH	AH
C_5	VH	M	M	VH	0	L	AH	H	AH	L
C_6	H	H	M	VH	L	0	AH	M	M	H
C_7	H	H	H	L	AH	AH	0	MH	L	M
C_8	M	VVH	H	VH	H	M	MH	0	M	M
C_9	VVH	M	VVH	VH	AH	M	L	M	0	H
C_{10}	VH	AH	VVH	AH	L	H	M	M	H	0
DM_2	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	0	VH	L	VH	VH	AH	H	VVH	VVH	H
C_2	VH	0	VVH	AH	MH	AH	AH	VH	AH	M
C_3	L	VVH	0	L	MH	AH	H	MH	L	M
C_4	VH	AH	L	0	AH	VH	H	H	H	H
C_5	VH	MH	MH	AH	0	M	M	H	H	VVH
C_6	AH	AH	AH	VH	M	0	AH	MH	AH	AH
C_7	H	AH	H	H	M	AH	0	M	VH	L
C_8	VVH	VH	MH	H	H	MH	M	0	H	MH
C_9	VVH	AH	L	H	H	AH	VH	H	0	M
C_{10}	H	M	M	H	VVH	AH	L	MH	M	0

Continue Table VI. The pairwise comparison decision matrix

DM_3	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	0	L	M	M	H	H	VVH	VVH	AH	AH
C_2	L	0	AH	AH	MH	L	AH	VH	H	H
C_3	M	AH	0	VH	L	VH	VH	AH	H	VVH
C_4	M	AH	VH	0	L	VH	VH	AH	H	VVH
C_5	H	MH	L	L	0	L	H	L	VH	H
C_6	H	L	VH	VH	L	0	L	M	M	H
C_7	VVH	AH	VH	VH	H	L	0	MH	MH	ML
C_8	VVH	VH	AH	AH	L	M	MH	0	L	ML
C_9	AH	H	H	H	VH	M	MH	L	0	L
C_{10}	AH	H	VVH	VVH	H	H	ML	ML	L	0

In addition, the criterion weights are computed based on Eqs. (17) – (31), as determined in Table VII. The final results show that the second criterion has a higher priority than the other indices. Table VIII shows M_k^+, M_k^- values, as well as the weights of the DMs (WD_k), which are computed based on Eqs. (39) – (41).

Table VII. The final criteria's weights

Criteria	Criteria's weights
C_1	0.08644
C_2	0.10901
C_3	0.08606
C_4	0.09938
C_5	0.10469
C_6	0.10518
C_7	0.10563
C_8	0.10519
C_9	0.10231
C_{10}	0.09611

Table VIII. The DMs' weights

DMs	M_k^+	M_k^-	WD_k
DM_1	0.90540	0.06499	0.32470
DM_2	0.90420	0.06635	0.33143
DM_3	0.90013	0.06872	0.34387

Table VIII shows that the third DM is superior to the other experts. Moreover, the IF- influence comparison decision matrix (P_{jj}) is determined in Table IX. Afterward, Table X depicts the values of A_i^k, E_i^k, E_{min}^k, and R_i^kusing Eqs. (42) – (45), respectively. Also, RF_i and the ranking of the alternatives are presented in Table XI based on Eqs. (46) and (47).

Table IX. The IF-influence comparison decision matrix

Criteria / DM_1	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	-0.67244	0.327561	0.327561	0.327561	0.327561	0.327561	0.327561	0.327561	0.327561	0.327561
C_2	0.227611	-0.77239	0.227611	0.227611	0.227611	0.227611	0.227611	0.227611	0.227611	0.227611
C_3	0.26345	0.26345	-0.73655	0.26345	0.26345	0.26345	0.26345	0.26345	0.26345	0.26345
C_4	-0.15884	-0.15884	-0.15884	-1.15884	-0.15884	-0.15884	-0.15884	-0.15884	-0.15884	-0.15884
C_5	0.022033	0.022033	0.022033	0.022033	-0.97797	0.022033	0.022033	0.022033	0.022033	0.022033
C_6	0.195375	0.195375	0.195375	0.195375	0.195375	-0.80462	0.195375	0.195375	0.195375	0.195375
C_7	0.271993	0.271993	0.271993	0.271993	0.271993	0.271993	-0.72801	0.271993	0.271993	0.271993
C_8	0.123568	0.123568	0.123568	0.123568	0.123568	0.123568	0.123568	-0.87643	0.123568	0.123568
C_9	0.084552	0.084552	0.084552	0.084552	0.084552	0.084552	0.084552	0.084552	-0.91545	0.084552
C_{10}	0.227326	0.227326	0.227326	0.227326	0.227326	0.227326	0.227326	0.227326	0.227326	-0.77267
DM_2	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	-0.49002	0.509983	0.509983	0.509983	0.509983	0.509983	0.509983	0.509983	0.509983	0.509983
C_2	0.200177	-0.79982	0.200177	0.200177	0.200177	0.200177	0.200177	0.200177	0.200177	0.200177
C_3	-0.60673	-0.60673	-1.60673	-0.60673	-0.60673	-0.60673	-0.60673	-0.60673	-0.60673	-0.60673
C_4	0.469385	0.469385	0.469385	-0.53062	0.469385	0.469385	0.469385	0.469385	0.469385	0.469385
C_5	0.169724	0.169724	0.169724	0.169724	-0.83028	0.169724	0.169724	0.169724	0.169724	0.169724
C_6	0.174463	0.174463	0.174463	0.174463	0.174463	-0.82554	0.174463	0.174463	0.174463	0.174463
C_7	0.078894	0.078894	0.078894	0.078894	0.078894	0.078894	-0.92111	0.078894	0.078894	0.078894
C_8	0.159547	0.159547	0.159547	0.159547	0.159547	0.159547	0.159547	-0.84045	0.159547	0.159547
C_9	0.477834	0.477834	0.477834	0.477834	0.477834	0.477834	0.477834	0.477834	-0.52217	0.477834
C_{10}	0.074435	0.074435	0.074435	0.074435	0.074435	0.074435	0.074435	0.074435	0.074435	-0.92557
DM_3	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	-1.0178	-0.0178	-0.0178	-0.0178	-0.0178	-0.0178	-0.0178	-0.0178	-0.0178	-0.0178
C_2	0.659358	-0.34064	0.659358	0.659358	0.659358	0.659358	0.659358	0.659358	0.659358	0.659358
C_3	0.118219	0.118219	-0.88178	0.118219	0.118219	0.118219	0.118219	0.118219	0.118219	0.118219
C_4	0.118219	0.118219	0.118219	-0.88178	0.118219	0.118219	0.118219	0.118219	0.118219	0.118219
C_5	0.428561	0.428561	0.428561	0.428561	-0.57144	0.428561	0.428561	0.428561	0.428561	0.428561
C_6	-0.65072	-0.65072	-0.65072	-0.65072	-0.65072	-1.65072	-0.65072	-0.65072	-0.65072	-0.65072
C_7	0.656712	0.656712	0.656712	0.656712	0.656712	0.656712	-0.34329	0.656712	0.656712	0.656712
C_8	-0.00365	-0.00365	-0.00365	-0.00365	-0.00365	-0.00365	-0.00365	-1.00365	-0.00365	-0.00365
C_9	0.364517	0.364517	0.364517	0.364517	0.364517	0.364517	0.364517	0.364517	-0.63548	0.364517
C_{10}	-0.08476	-0.08476	-0.08476	-0.08476	-0.08476	-0.08476	-0.08476	-0.08476	-0.08476	-1.08476

Table X. The obtained ranking values of the alternatives

DM_1	A_i^k	E_i^k	E_{min}^k	R_i^k
A_1	[0.24492,0.26864]	[0.01922,0.02403]	[0.01922,0.02403]	[0.24610,0.27027]
A_2	[0.25583,0.27926]	[0.01922,0.02403]		[0.25699,0.28087]
A_3	[0.28923,0.31063]	[0.04133,0.04325]		[0.29034,0.31216]
DM_2				
A_1	[0.34298,0.35906]	[0.04133,0.04325]	[0.03364,0.03845]	[0.34560,0.36220]
A_2	[0.31107,0.33410]	[0.03364,0.03845]		[0.31381,0.33736]
A_3	[0.28594,0.31172]	[0.04133,0.04325]		[0.28878,0.31509]
DM_3				
A_1	[0.30190,0.32305]	[0.04325,0.04517]	[0.01922,0.02403]	[0.30335,0.32494]
A_2	[0.31901,0.34359]	[0.04325,0.04517]		[0.32042,0.34543]
A_3	[0.32297,0.34305]	[0.01922,0.02403]		[0.32437,0.34489]

Table XI. Final ranking of the alternatives

Alternatives	RF_i	UT_i	Final ranked
A_1	[0.29595,0.31729]	%98.10	3
A_2	[0.29622,0.32047]	%98.65	2
A_3	[0.30108,0.32405]	100.00%	1

The results indicate that the third project, as metro development with intelligent urban mobility and research-driven design solutions, achieves the highest utility degree, mainly due to its strong technological capability and policy alignment. For managers, this implies that projects with stable governmental support and clear technological roadmaps should receive priority in R&D PPP portfolios.

IV. DISCUSSION

A. Comparative Analysis

In this section, to evaluate the efficiency of the proposed method, we compare it with the IF-TOPSIS method. By solving the problem using IF-TOPSIS, the values of the points and parameters change, but the final result, the final ranking of the options, remains identical to that of the proposed method. This indicates the high performance of the proposed method for R&D-oriented PPP project selection, providing significant assistance to management levels and DMs in this area. Additionally, the comparison among four methods (IF-TOPSIS, IF-VIKOR, IF-COPRAS, and the proposed method) in ranking the alternatives is presented in Table XII.

Table XII. The comparison between the two approaches

Alternatives	Values of the IF-TOPSIS	TOPSIS ranked	IF-VIKOR	IF-VIKOR ranked	IF-COPRAS	IF-COPRAS ranked	Proposed method ranked
A_1	0.89452	3	0.0735	2	93.8%	3	3
A_2	0.89734	2	0.3977	3	94.6%	2	2
A_3	0.90145	1	0.0045	1	100%	1	1

The results demonstrate that the ranking obtained by our proposed IFWG-based approach is consistent with those of the compared methods regarding the best alternative (A3), confirming the robustness of the proposed model. Minor variations in the order of the second and third alternatives are observed across methods, which is a well-known and expected phenomenon in MCDM comparison studies, attributable to differences in the underlying aggregation philosophies of each method. The extended results are presented in the revised Section 5 and Table XII.

B. Sensitivity Analysis

1. Criteria weights analysis

To evaluate the robustness of the proposed decision framework, a weight-perturbation sensitivity analysis was conducted. Unlike the comparison with IF-TOPSIS, which serves as a comparative validation exercise, this analysis directly examines the effect of changes in criterion weights on the final ranking of alternatives. Since C_2 received the highest aggregated importance weight in the proposed framework, its weight was selected for perturbation. Five scenarios were considered: the baseline case and four perturbed cases in which the original weight of C_2 was decreased and increased by 10% and 20%, respectively. To preserve the normalization condition, the weights of all remaining criteria were proportionally adjusted after each change in the weight of C_2. The final ranking of alternatives was recalculated for every scenario using the proposed intuitionistic fuzzy decision procedure. As reported in Table XIII, the ranking remains unchanged in all five scenarios, namely A3 ≻ A2 ≻ A1. Therefore, the proposed model demonstrates satisfactory robustness against moderate variations in the weight of the most important criterion.

Table XIII. Sensitivity of the final alternative ranking to changes in the weight of C2

Scenario	Change % in C2	W_{C1}	W_{C2}	W_{C3}	W_{C4}	W_{C5}	W_{C6}	W_{C7}	W_{C8}	W_{C9}	W_{C10}	Final Ranking
S_0	-20.%	0.09	0.09	0.09	0.1	0.11	0.11	0.11	0.11	0.1	0.1	A3 > A2 > A1
S_1	-10.%	0.09	0.1	0.09	0.1	0.11	0.11	0.11	0.11	0.1	0.1	A3 > A2 > A1
S_2	0.%	0.09	0.11	0.09	0.1	0.1	0.11	0.11	0.11	0.1	0.1	A3 > A2 > A1
S_3	10.%	0.09	0.12	0.09	0.1	0.1	0.1	0.1	0.1	0.1	0.09	A3 > A2 > A1
S_4	20.%	0.08	0.13	0.08	0.1	0.1	0.1	0.1	0.1	0.1	0.09	A3 > A2 > A1

2. DM weights analysis

To examine the influence of the DM-weighting procedure on the final results, a sensitivity analysis was performed. Specifically, the DM weights obtained through the CS approach (w_{DM1} = 0.324, w_{DM2} = 0.331, w_{DM3} = 0.343) were compared with the case of equal DM weights (w_{DMk} = 1/3 for all k). The analysis showed that the final ranking of the alternatives remained unchanged under both weighting schemes.

C. Managerial and Practical Implications

The proposed approach serves a wide range of stakeholders by providing actionable insights for informed decision-making in R&D-oriented PPP projects.

First, public-sector DMs and policy planners can use the framework to select projects through a transparent and reproducible quantitative process. This helps them justify their choices and allocate limited public resources to projects with the highest probability of success and strongest strategic alignment with national development goals.

Second, private-sector partners and investors often face high-risk conditions in R&D-oriented PPPs. The proposed methodology enables a more rigorous assessment of risk and returns by incorporating expert judgments under intuitionistic fuzzy uncertainty. It can therefore serve as a screening tool for identifying projects where private participation is more strategically justified.

Third, project managers and R&D portfolio directors can use the model to address the complexity of interdependent criteria. By quantifying the influence relationships among criteria through the integration of IF-DEMATEL and IF-ANP, the framework helps identify critical performance bottlenecks and prioritize the factors that most affect project success.

Fourth, academic researchers and methodologists may benefit from the proposed ranking procedure, particularly the IF-CS-based weighting and the new intuitionistic fuzzy ranking approach. These contributions provide a robust alternative for multi-criteria decision-making problems characterized by uncertainty and interdependence.

Overall, the framework offers several practical implications for R&D-oriented PPP project selection. The hybrid IF-ANP and IF-DEMATEL structure makes it possible to capture criterion interdependencies that are often ignored in conventional MCDM methods. In real-world PPP settings, criteria such as technological capability, financial viability, and policy alignment are not independent; neglecting these interactions may lead to biased rankings and inefficient resource allocation. The intuitionistic fuzzy environment also allows DMs to represent hesitation and uncertainty in expert judgments, which is particularly valuable in early-stage R&D projects where quantitative data are limited. Finally, the proposed utility degree provides a transparent and interpretable basis for ranking alternatives and communicating results among stakeholders with different backgrounds.

V. CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH

Large-scale infrastructure projects play a central role in socioeconomic development and improving quality of life, but their implementation typically involves substantial capital requirements, technological uncertainty, and financial risk. Public–private partnerships (PPPs) can mitigate some of these challenges by combining public oversight with private-sector capital, expertise, and operational capabilities. As urban infrastructure increasingly shifts toward smart, sustainable, and technology-intensive systems, the selection of R&D-oriented PPP projects requires the simultaneous consideration of conventional financial and operational criteria alongside R&D-specific factors, including innovation capacity, technological feasibility, and knowledge transfer.

To support this decision problem, this study developed an intuitionistic fuzzy multi-criteria group decision-making framework integrating IF-ANP, IF-DEMATEL, IF-CS, and a new intuitionistic fuzzy ranking procedure. The integration of IF-ANP and IF-DEMATEL was used to determine the weights of interdependent criteria while accounting for their feedback relationships and mutual influences. The IF-CS component was employed to derive the relative weights of the DMs based on their assessments, thereby supporting the aggregation of heterogeneous expert opinions. Finally, the proposed ranking procedure combines the weighted evaluations to determine the priority order of the candidate projects under intuitionistic fuzzy uncertainty.

The main findings of the case study can be summarized as follows. First, the results show that explicitly considering criterion interdependence can influence the evaluation structure and final priorities of R&D-oriented PPP projects. This finding is important because the relevant financial, technological, strategic, and operational criteria do not operate independently in practice. Second, the intuitionistic fuzzy representation enabled the model to retain both the expressed assessments and the hesitation embedded in expert judgments, which is particularly relevant when historical and quantitative information on the innovative infrastructure projects is limited. Third, the case-study results ranked intelligent metro development (A_3) as the most preferable alternative, followed by innovative bridge construction (A_2) and smart-highway construction (A_1). Thus, the final ranking was:

This result indicates that, under the criteria, judgments, and assumptions adopted in the case study, the intelligent metro project offered the most favorable overall balance among the evaluated dimensions. The comparative analysis with the conventional IF-TOPSIS method and the literature-based benchmarks also showed that the proposed framework produced a stable and discriminative prioritization of the alternatives. Collectively, these results support the central expectation of the study that the simultaneous treatment of criterion interdependence, expert hesitation, and heterogeneous decision-maker contributions can provide a more comprehensive basis for R&D-oriented PPP project selection.

From a managerial standpoint, the proposed framework provides public-sector DMs, private investors, project managers, and R&D portfolio directors with a structured and transparent decision-support procedure. Public authorities can use the results to justify project priorities and allocate limited resources in line with strategic development objectives. Private partners and investors can employ the framework to screen candidate projects and assess their strategic suitability under uncertain conditions. Project managers can use the influence relationships and criterion weights to identify the factors that require greater managerial attention. In addition, the final utility values and project rankings provide a traceable basis for discussing and communicating project priorities among stakeholders with different interests and areas of expertise.

Despite these contributions, the study has several limitations. First, the empirical application was based on a single urban infrastructure case involving a limited number of candidate projects, criteria, and expert DMs. Therefore, the resulting ranking reflects the characteristics and judgment structure of the examined case and should not be generalized to all R&D-oriented PPP environments without further validation. Second, the criteria and expert assessments were considered within a static decision setting. Possible changes in technological readiness, financing conditions, regulatory requirements, and stakeholder preferences over the project life cycle were not explicitly modeled. Third, although intuitionistic fuzzy sets represent membership, non-membership, and hesitation, they may not capture all forms of ambiguity or complex linguistic behavior in expert assessments. Fourth, the framework relies primarily on expert-based evaluations; consequently, its results may remain sensitive to the composition, experience, and judgment consistency of the expert panel. Finally, the study focused on ranking individual alternatives and did not incorporate budget limitations, project interactions, or portfolio-level resource-allocation constraints.

These limitations suggest several specific directions for future research. First, the framework could be evaluated using larger expert panels, broader sets of alternatives, and multiple case studies across different institutional and geographical settings. Cross-case applications would enable researchers to examine the stability and generalizability of the resulting criterion weights and project rankings. Second, subjective expert-based weights could be combined with objective weighting techniques, such as intuitionistic fuzzy entropy, using actual financial, technological, environmental, and operational data. Such an integration would provide a more balanced weighting structure and allow the effects of subjective and data-driven information to be compared. Third, a dynamic or longitudinal version of the framework could be developed to update criterion weights and project priorities as technological readiness, market conditions, regulatory policies, and stakeholder preferences evolve over time. Fourth, alternative uncertainty representations, including picture fuzzy sets, spherical fuzzy sets, and hesitant fuzzy linguistic term sets, could be incorporated and empirically compared to determine whether they provide additional explanatory or discriminatory power. Fifth, the proposed ranking procedure could be integrated with multi-objective mathematical programming to construct PPP project portfolios subject to budget, risk, scheduling, and resource constraints. Finally, applications in renewable energy investment, smart-grid deployment, digital healthcare infrastructure, and other technology-intensive sectors would help assess the transferability and practical value of the proposed framework beyond the urban infrastructure context.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article.

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