mathematics

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A Hybrid Fuzzy MCDM Approach to Open Innovation Partner Evaluation

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Abstract: Even though interest in open innovation (OI) both as a research field and as an industrial practice for creating competitively advantageous innovation through collaboration has grown exponentially over the last decades, the issue of how to transform OI strategy into a sustainable competitive advantage is still an open research question. Selecting partners capable of operationally and strategically contributing to the OI project goals is a strategic decision for companies striving to effectively implement the OI concept. The study is aimed at defining a structured and methodology-supported decision-making process for OI partner selection based on a novel hybrid Multi-Criteria Decision-Making (MCDM) model which is enhanced by interval type-2 fuzzy sets (IT2F) to deal with the inherent uncertainty. The model combines IT2F Delphi (IT2FD), IT2F Analytical Hierarchy Process (IT2F AHP), and IT2F Preference Ranking Organization METHod for Enrichment of Evaluations (IT2F PROMETHEE). The study provides a comprehensive framework of the OI partner performance indicators; additionally, it provides a contingent approach to identifying evaluation criteria depending on the nature of the company's innovation processes, contextual conditions, and innovation strategy. The case study is used to verify the feasibility and effectiveness of the proposed process. The study's results highlight the significance of specific factors related to the partners' technological competencies.

Keywords: open innovation projects; MCDM; IT2FD; IT2F AHP; IT2F PROMETHEE

MSC: 90B50

Citation: Puzović, S.; Vesić Vasović, J.; Milanović, D.D.; Paunović, V. A Hybrid Fuzzy MCDM Approach to Open Innovation Partner Evaluation. *Mathematics* **2023**, *11*, 3168. https://doi.org/10.3390/math11143168

Academic Editor: Ignacio Javier Perez Galvez

Received: 25 June 2023
Revised: 14 July 2023
Accepted: 17 July 2023
Published: 19 July 2023

1. Introduction

Increased technological complexity, a fusion of different technologies, resource scarcity, and market unpredictability have resulted in companies adopting a more open, cooperative approach to generating competitive advantage [1,2], which has led to more flexible business models based on more open interactions with the external environment. This prompted companies to transform their centralized research and development (R&D) systems by spreading their innovation processes across a global network of external partners and locations [3,4].

Dominantly closed innovation systems, exclusively concentrated inside organizational boundaries, have proven to be unsustainable, unreliable, rigid, costly, too sluggish, and incapable of generating technologically superior and market-sustainable innovations. Instead, companies are encouraged to use input from outsiders and find external opportunities for the commercialization of products and technologies to strengthen internal innovation processes [5].

This gave birth to the concept of open innovation (OI), introducing a radical transition in the way companies manage their innovation processes. OI is defined as a distributed innovation process that relies on purposefully managed knowledge flows across organizational boundaries, using pecuniary and nonpecuniary mechanisms in line with the business model to guide and motivate knowledge sharing [6].

Such relations tend to combine complementary resources and build synergies while simultaneously being characterized by an intensive exchange of knowledge and learning processes [7]. The OI concept enables companies to be more efficient in terms of creating and capturing value, collective intelligence acquisition, saving costs and time, and accelerating new revenue opportunities. It also enables overcoming geographical, institutional, and disciplinary barriers thanks to the openness of research and development, the diffusion of technology, and the open exchange of knowledge [6,8].

The OI concept has evolved into one of today's most important business paradigms. According to Bogers et al. [9], OI will play a critical role in the world's developed economies in the coming decades. They cite new technological trends such as blockchain and digitalization, genome editing, and sustainable development goals promoted at the international level as key incentives for OI. OI is also often mentioned as an accelerant of the new industrial initiative Industry 4.0. In fact, according to Hizam-Hanafiah and Soomro [10], the OI and initiatives referring to the external exploitation of knowledge are fully in line with the needs of an integrated digital business model.

These trends encourage companies to implement the OI paradigm through partnerships and collaborations among firms in R&D projects. Relying on key OI principles such as the use of external ideas and technologies that reduce R&D costs and time while improving the overall efficiency of the company and the ability to acquire, perceive, and use new knowledge faster than competitors [11].

Despite the fact that interest in the OI concept in the creation of technological innovations as a field of research has grown exponentially during the last decades, the questions of how to promote the adaptation of companies to OI practices and how to transform an OI strategy into a sustainable competitive advantage remain open research questions. Namely, Carmona-Lavadoa et al. [12] argue that openness in itself cannot be a determinant of performance unless it is supported by complementary means, such as coordination ability and complementarity of innovation partners, which, it turns out, are essential in ensuring the successful transfer and integration of critical know-how and in creating value through collaboration [13].

Although methods and strategies for establishing cooperation between innovation partners have been the subject matter of interest for many research studies [14,15], the studies pertaining to the development of methodologically supported approaches to OI optimal partner selection have not led to the development of a dominant reference approach; consequently, this process, in practice, is still mostly carried out on an ad hoc basis.

Current methodological approaches in this area have several deficiencies to some extent, including: a lack of the necessary holistic approach; a lack of operational indications; a lack of flexibility in the system of evaluation criteria to take into account the company's business circumstances, innovation policies, or strategies; and a lack of systematized and structured decision-making process.

The OI partner selection problem can be analyzed in a multi-dimensional space of different parameters and objectives in order to cope with complexity; as such, it could be considered a multi-criteria decision-making (MCDM) problem. The use of MCDM methods for these problems could provide a reliable compromising solution regarding various objectives, aspects, and criteria. It provides some advantages such as integrating a large number of different and often conflicting criteria and making alternatives evaluation much more flexible, objective, and acceptable.

In addition, when a detailed literature review is made it is seen that there are many different application areas of MCDM techniques for OI management-related issues. MCDM applications in the OI environment are comprehensively reviewed; Table 1 denotes the papers with a research focus on the application of MCDM methods to OI management-related issues.

Table 1. Application of MCDM Methods in the OI Environment.

MCDM Methods	Research Focus	Studies
Fuzzy AHP	Collaboration network partner selection with integration business, social, and environmental goals	[16]
Fuzzy AHP	Evaluation of process of innovation-oriented knowledge under the open innovation paradigm	[17]
Fuzzy Delphi, Fuzzy DEMATEL, DANP	Prioritizing and analyzing interrelationships among factors affecting Foreign Direct Investment attractiveness and open innovation	[18]
Fuzzy TOPSIS	Ranking the indicators of open innovation adoption based on new product development factors	[19]
Fuzzy AHP, Fuzzy VIKOR	Determination of an appropriate open innovation model for logistics firms	[20]
Delphi, Fuzzy ANP	End-to-end analysis of an open innovation setup for determining a suitable innovation structure	[21]
ANP, PROMETHEE	Ranking the moderating factors that have contributed to the degree of small and mid-size enterprises' participation in open innovation activities	[22]
DEMATEL	Determination the best ranking of effective factors in open innovation success in manufacturing enterprises	[23]
AHP ISM	Investigation mechanisms for improving supply chain open innovation networks	[24]
IT2F AHP	Supporting the effective selection of partners for collaborative technological R&D projects	[25]

Analytic Network Process: ANP; Analytical Hierarchy Process: AHP; DEMATEL-based Analytic Network Process: DANP; Decision-Making Trial and Evaluation Laboratory: DEMATEL; Interpretative Structural Modeling: ISM; Interval Type-2 Fuzzy: IT2F; Preference Ranking Organization METHod for Enrichment of Evaluations: PROMETHEE; Technique for the Order Preference by Similarity to Ideal Solution: TOPSIS; VIšeKriterijumska Optimizacija i kompromisno Rešenje: VIKOR.

The paper introduces a hybrid MCDM model for OI partner selection that provides a systematic and structured approach that may facilitate the generation of relevant decision-making factors and an assessment of the relative importance of various decision-making elements.

The study provides a certain methodological advancement in OI partner selection. First, a comprehensive framework of OI partner performance indicators is provided, encompassing the essential technological, operational, and strategic evaluation aspects. In addition, it provides a contingent approach to identifying OI partner evaluation criteria, considering the nature of the company's innovation processes, contextual conditions, and innovation strategy.

The increasing complexity of the social and economic environment, along with the vagueness of the inherently subjective nature of human thinking, leads to the impossibility of describing the input data of the decision-making process with crisp values [26]. Given the capabilities of interval type-2 fuzzy (IT2F) sets in representing vague preferences and dealing with the hesitation of human perception, the proposed MCDM model is extended in the context of the IT2F set theory to make the proposed approach more convenient for modeling different sources of vagueness and uncertainty in real-life decision-making problems.

The rest of the paper is organized as follows: The problem of OI partner selection is analyzed in Section 2, with a literature review. Section 3 presents the theoretical basis of the methods involved in this paper and describes the proposed decision-making process. In Section 4, a case study is presented to help understand the methodology proposed for OI partner selection and demonstrate its practicality and feasibility. Finally, discussion and directions for future research are presented in Section 5.

2. The Problem of OI Partner Selection

The various types of methodological support developed thus far lack the necessary holistic approach and thus only reflect the relationships between OI partners superficially.

Otherwise, it is difficult to follow them from the perspective of an enterprise due to a lack of operational indications, for which they require great expertise and experience on the analyst's part. Additionally, they often provide generic systems of criteria, whereby their adaptability to the company's business circumstances, innovation policies, and strategies has not been given much attention.

A significant number of the studies dealing with this issue are directed towards the development of methodologies intended to discover data about potential partners, whose contribution is limited to providing support for their identification and the analysis of their competencies and capacities but does not provide systematized and structured approaches for making the final decision on partner selection.

Yoon and Song [27] identify three methodological approaches in OI partner selection, namely: (1) the mathematical programming methods that deal with the theoretical process for formulating variables and equations; (2) the approaches to the evaluation and ranking based upon the analyst's evaluations; and (3) the approaches based upon the application of the artificial intelligence techniques that served to process a large amount of data to find a well-matched partner.

The approaches to evaluation and ranking based on the analyst's evaluations are the most suitable to apply in the practical operations of an enterprise. The academic and professional literature, however, lacks consensus on which aspects of potential partner evaluation should be included in deciding on the selection. In that context, several characteristic approaches are possible to identify.

The first group consists of approaches exclusively limited to the technological aspects of partner competency and complementarity while simultaneously most frequently relying on the analysis of information about registered patents, which in this case are considered to be the most relevant data for researching the innovation activities of potential partners. For example, Manotungvorapun and Gerdsri [28] propose an approach that utilizes patent information by applying morphology analysis and generative topology maps. Park and Yoon [29] used a multistage patent citation analysis method that included bibliographic coupling and the keyword vector mapping information visualization method. Wang [30] and Jeon et al. [31] take a similar approach.

The approaches based on the consideration of partners' technological compatibility illustrate the affinity for their technological knowledge [32] and may be suitable if technologies are becoming increasingly complex or distributed over various sources, or when technology fusion is recognized as an important part of collaborative innovation [31]. They are, however, criticized for excluding taking the strategic perspective into account.

Many authors point out the need for a multidimensional assessment, namely, beside technical compatibility as an indicator of the compatibility of the relevant knowledge and technology capabilities that determine the absorptive potential, an important emphasis is placed on nontechnical compatibility as well as the indicators of the congruence of the goals and the cooperation process, which affect the stability and organizational harmonization of OI partner relations and generate trust and commitment [33–35]. Namely, OI success does not only depend on the efficient integration of internal and external technologies and types of knowledge, but it also depends on factors such as strategic goals, organizational culture, the R&D strategy, the top management style, an attitude towards cooperation in R&D activities, the innovation partners' protocols, and the innovation environment [28,30]. Büyüközkan et al. [36] emphasize that two dimensions should necessarily be included in potential partner assessment: the first pertaining to their strategic excellence and the second pertaining to their business, i.e., their operational excellence. Holmberg and Cummings [37] suggest that, when selecting OI partners, potential partners' motivation for innovation cooperation must be considered apart from the criteria related to the partners' attributes [38].

Consistent evaluation outcomes necessitate the use of the contingent system of evaluation criteria, which could be adapted to the company's business circumstances, innovation policies, and strategies. According to Shah and Swaminathan [39], if the interpretability of the OI project outcome is low, i.e., if there are limited possibilities of interpreting and understanding them, priority should be given to the criteria pertaining to the compatibility of the identity, culture, goals, mutual trust, and so forth. The same is also applicable if it is difficult to establish control over the process. On the contrary, outcome-oriented criteria (such as financial cost-effectiveness) will dominate in OI partner selection. According to Sarkar et al. [40], if the OI aim is focused on achieving product novelty or technological superiority, the technological complementarity criteria should be prioritized. If the emphasis is on accelerating and smoothing the innovation process and establishing a supportive collaborative environment, nontechnical criteria are heavily weighted.

3. Materials and Methods

The study contributes to the development of an improved decision-making methodology framework for OI partner selection, and the following are some benefits that are represented in it:

(i) For the first time, a comprehensive framework of OI partner performance indicators is provided, consisting of five critical dimensions and twenty-seven indicators, encompassing all relevant technological, operational, and strategic evaluation aspects.

(ii) The novel hybrid IT2F MCDM model combining IT2FD, IT2F AHP, and IT2F PROMETHEE is established, which provides a contingent approach to identifying OI partner evaluation criteria considering the nature of the company's innovation processes, contextual conditions, and innovation strategy; and yields precise multi-criteria alternatives evaluation under a high uncertainty level.

This results in a structured and methodology-supported, five-stage decision-making process for OI partner selection. In addition, by identifying the key OI partners' performance indicators, the study offers valuable guidance for managers in generating management strategies and best practices to maximize synergy of collaboration in OI projects.

The study primarily provides a comprehensive framework that encompasses all relevant technological, operational, and strategic aspects of OI partner evaluation, ensuring a holistic approach to the problem. This leads to a more integrated and coherent list of potential OI partner evaluation criteria (Table 2). The research process included a review of the existing methodological frameworks for decision support in the selection of OI partners, studies on inter-organizational knowledge transfer and generation, as well as studies on inter-organizational relationships, from which the key indicators that model the quality of cooperation among OI partners have been identified. As a result, five critical dimensions were identified, including (i) technological competencies; (ii) resource complementarity; (iii) financial terms of collaboration; (iv) cooperative capability; and (v) strategic alignments. A comprehensive set of twenty-seven indicators of OI partner performance covering these five dimensions was established.

In parallel with the literature analysis, as a second part of the research process, interviews were conducted with 18 managers with at least two years of experience in managing OI projects and an engineering or business academic background. The managers were asked to state the factors that, in their opinion, had the most significant influence on the quality of partner cooperation during the OI projects they were involved in. After revising the collected statements and rationalizing the different nomenclature, it was concluded that the indicators recommended by the practitioners are already included in the literature review-defined list.

Table 2. The potential OI partner evaluation criteria list.

Criteria		Studies
Technological competencies	Technological innovation level	[41,42]
	Technological complementarity	[34]
	Product experience	[43]
	Number of patents held	[27]
	Expected capabilities of abstraction	[43]
	Technology transfer capability	[44]
Resource complementarity	Overlapping knowledge base	[35]
	Product-specific knowledge	[45]
	Market knowledge complementarity	[35,45]
	Expected knowledge maturity	[43]
	Past experiences	[34]
	Financial assets	[45]
Financial terms	Expected debt ratio and refund ability	[46]
	Financial resources demand of the project	[34]
	Return of investment	[46]
Cooperative capability	Collaborative behavior	[28]
	Mutual trust and commitment	[35,39,45,47,48]
	Management and organizational culture	[34,35,42,46,49,50]
	Previous relationship	[28]
	Propensity to change	[35]
	Geographical proximity	[28,43]
	Symmetry of scale and scope	[45,46]
Strategic alignments	Compatibility of corporation strategies	[46]
	Convergence of expectations between partners	[34]
	Motivation and goal correspondence	[35,50]
	Strategic objectives of intellectual property management	[28]
	Market complementarity	[34]

The proposed methodology framework is implemented in a five-phase hybrid process (Figure 1) combining the advantages of three methods, namely Delphi, the Analytical Hierarchy Process (AHP), and the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE). As far as we know, this is the first time the proposed hybrid MCDM model has been applied.

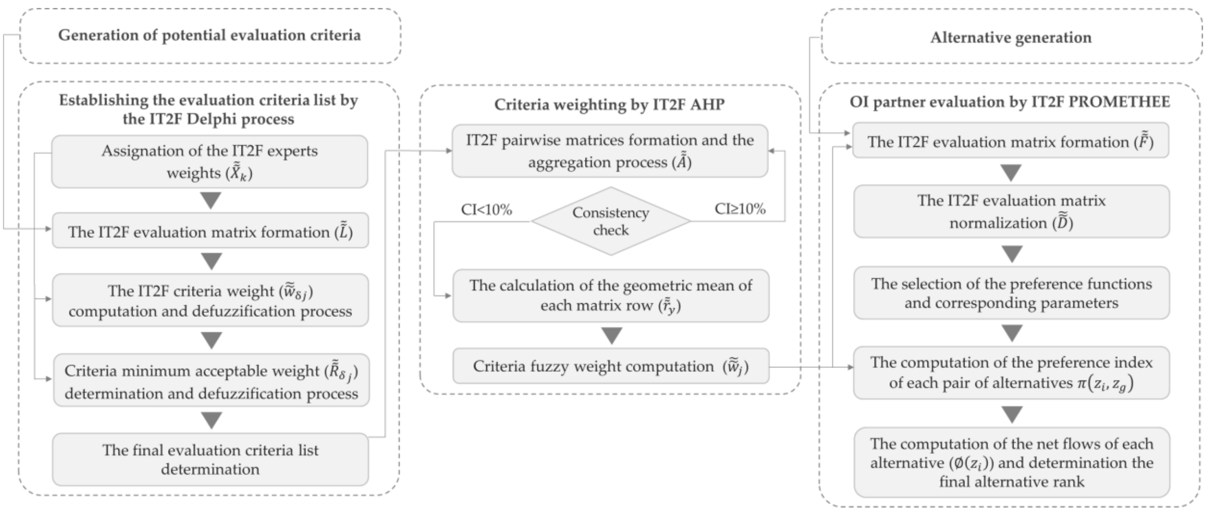

Figure 1. The proposed methodology framework.

The synthesis of the conventional Delphi approach and the IT2F set theory (IT2FD) enables the inclusion of expert subjective judgments, enabling a more comprehensive and inclusive approach to elicit the most essential evaluation criteria from the list of potential ones (Table 2), depending on the nature of the company's innovation processes as well as the contextual conditions and the corporate innovation strategy. The proposed IT2FD process results in a contingent and reliable set of OI partner performance indicators, enhancing the validity and practicality of the chosen evaluation criteria in OI partner selection. It provides companies with a way to optimize the evaluation criteria and make consistent decisions.

The framework also provides a methodology for rational and reliable criteria weighting based on the vague linguistic evaluations of multiple experts by applying the IT2F AHP approach. The strength of this method is based on the ability to express preferences using linguistic statements, which is more similar to the human way of thinking, the concept of systematic pairwise criteria comparison, and a mathematically simple synthesis of the obtained results for deriving criteria weights. Additionally, the framework incorporates the methodology for multi-criteria evaluation and ranking of alternative OI partners based on the IT2F PROMETHEE approach, which is suitable for solving complex decision-making problems that require a range of human perceptions and judgments, especially when there are significant differences in participants' perceptions of the decision-making process. Moreover, the criteria properties are treated in a proper way by involving different types of preference functions as well as the associated parameters for each criterion.

The conventional forms of the MCDM methods, modeled with crisp input data, are incompatible with the human thinking process, rendering them inapplicable under the highly vague and uncertain decision environment derived by the subjective nature of the preferences, the impossibility of expressing preference relations using crisp measures, the hesitation of human perception, and a lack of quantitative criteria.

A typical MCDM problem involves several qualitative and quantitative measurements. Given the fact that these measurements are frequently impossible to be precisely presented and precisely anticipated based upon objective pieces of information or directly and analytically explained, they will instead be based on the objective assessments made by the representatives of personalized types of knowledge and experiences specific to a particular criterion. Modeling the uncertainties and imprecisions that arise in that case in this study is performed by the application of the mathematical models developed in an IT2F environment.

To efficiently resolve the ambiguity frequently arising from the available pieces of information and to do more justice to the essential vagueness in human judgment and preference, fuzzy set theory is used to establish ill-defined MCDM problems [51]. Indubitably, the value of the MCDM methods will be improved if the properties of human adaptively, intransitivity, and dynamic adjustment of preferences can be considered in the decision process [52]. Fuzzy set theory is oriented towards the conversion of human perceptions given as linguistic statements into an arithmetical form by representing vague data using fuzzy numbers [51].

The literature notes a large number of different MCDM models integrated with fuzzy sets theory used for modeling uncertain and imprecise data in different decision-making problems [53–60]. Moreover, some studies [26,61] that provide insight into research in the field of MCDM encompassing the application of IT2F sets, confirm the high level of use of IT2F sets-based MCDM models in the domains of engineering and management, assuming that the trend in research in IT2F MCDM will remain stable in the future.

3.1. Multi-Criteria Decision-Making and Interval Type-2 Fuzzy Sets

Due to the power of fuzzy logic to overcome the problems of indeterminacy and inconsistency, fuzzy sets are used in decision-making processes in which their application allows decision-makers to convert the linguistic terms or responses to be evaluated with a degree of certainty [62]. To accommodate ambiguity, fuzzy sets allow for membership inside an interval between two real values. Accordingly, fuzzy sets allow decision-making problems to be resolved in a more flexible and precise manner.

The choice the shape of the membership function can be considered a problem in itself. A special case of generalized type-2 fuzzy IT2F sets has been seen as the most useful since they are more manageable in terms of calculations [63]. Moreover, IT2F sets are often chosen as a viable alternative due to their numerous superiorities over conventional type-1 fuzzy sets. Namely, in IT2F sets, linguistic statements are modeled more efficiently in comparison to type-1 fuzzy sets, which are defined with a two-dimensional membership function, while the IT2F set membership function is three-dimensional, providing additional degrees of freedom for better dealing with vague data. Therefore, type-2 fuzzy sets are proposed [64] as more applicable to real-life decision-making problems.

IT2F sets have been successfully implemented with MCDM methods that involve expressing decision-makers' preferences using a linguistic scale to fully describe the inherent uncertainties, and make it more convenient for applying in a highly vague and uncertain decision-making environment. In the past two decades, research in the field of IT2F MCDM has experienced intense growth. So far, a large number of studies have been focused on the development and implementation of IT2F MCDM models for real-world problems in an uncertain and ambiguous environment.

Mathew et al. [55] introduced the IT2F MCDM model based on the AHP and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), which can effectively handle the degree of uncertainty in group decision-making process of selecting the optimal industrial asset maintenance strategy. Ecer [56] utilized an extension to AHP under an IT2F environment to better cope with ambiguity for supplier selection, considering green concepts. The study [25] employed the same approach, aimed at supporting the effective selection of partners for collaborative technological R&D projects. Gölcük [65] introduced a novel risk assessment model by combining the IT2F Best–Worst Method (BWM) with perceptual reasoning for the evaluation of risk in digital transformation projects. Wu et al. [66] proposed an investment decision-making framework based on IT2F sets and the PROMETHEE-II model. In the study [67], the IT2F-based MCDM approach established by integrating TOPSIS and Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods is utilized for the SWOT-based strategy selection problem by means of preparatory efforts to develop a renewed strategic plan for the industrial engineering department. Boral et al. [68] suggested a novel integrated framework comprising IT2F AHP, IT2F DEMATEL, and IT2F Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS) for prioritizing the risks associated with human error in the context of Failure Modes and Effects Analysis (FMEA)-based risk analysis approach. Bera et al. [69] used Multi-Objective Optimization on the basis of Ratio Analysis (MOORA) and TOPSIS methods in an IT2F environment for supplier selection, considering both subjective and objective factors. Karagöz et al. [70] utilized an extension of the Additive Ratio ASsessment (ARAS) method under the IT2F environment for solving the end-of-life vehicle recycling facility location problem. The study [71] constructs a barrier evaluation framework for forest carbon sink project implementation by introducing a hybrid MCDM model encompassing the BWM and PROMETHEE II in the IT2F environment.

3.2. Interval Type-2 Fuzzy Sets

The interval type-2 fuzzy (IT2F) sets, first introduced by Zadeh [64], are defined by the interval, a three-dimensional membership function that is fuzzy by itself, which makes it much more competent for modeling the ambiguities inherent to MCDM problems since it is described by both the primary and the secondary membership functions, which provides a higher degree of flexibility. According to Mendel and John [72], the main sources of these ambiguities include:

- The meanings of the used linguistic terms and the consequences of the rules can be uncertain;
- Consequents may have a histogram of the values associated with them, especially when knowledge is extracted from a group of experts who do not have a unified attitude;
- The measurements that activate type-1 fuzzy logic may be uncertain;
- The data used to tune the parameters of the type-1 fuzzy logic system may be noisy.

According to Aleksic and Tadic [26], handling uncertainties by using type-2 numbers implies making fewer assumptions, which results in more realistic solutions to real-life decision-making problems.

In the following, a brief review of some definitions of IT2F sets is presented [63].

Definition 1. *Let $(\stackrel{\approx}{A})$ be a type-2 fuzzy number characterized by the membership function $\mu_{\stackrel{\approx}{A}}(x,u)$:*

$$\stackrel{\approx}{A} = \left\{ \left((x,u), \mu_{\stackrel{\approx}{A}}(x,u) \right) \forall x \in X,\ \forall u \in J_x \subseteq [0,1], 0 \leq \mu_{\stackrel{\approx}{A}}(x,u) \leq 1 \right\} \tag{1}$$

which can also be interpreted as in Equation (2).

$$\begin{gathered} \stackrel{\approx}{A} = \int_{x \in X} \int_{u \in J_x} \frac{\mu_{\stackrel{\approx}{A}}(x,u)}{(x,u)}, J_x \subseteq [0,1] = \int_{x \in X} \left[\int_{u \in \int_x} \frac{\mu_{\stackrel{\approx}{A}}(x,u)}{u} \right] / x \\ UMF\left(\stackrel{\approx}{A}\right) = sup\left\{ u \middle| u \in [0,1], \mu_{\stackrel{\approx}{A}}(x,u) > 0 \right\}, \forall x \in X \\ LMF\left(\stackrel{\approx}{A}\right) = inf\left\{ u \middle| u \in [0,1], \mu_{\stackrel{\approx}{A}}(x,u) > 0 \right\}, \forall x \in X \end{gathered} \tag{2}$$

Definition 2. *If it is further assumed that each $\mu_{\stackrel{\approx}{A}}(x,u)$ is equal to 1, then $\stackrel{\approx}{A}$ can be considered as an IT2F number which can be interpreted as in Equations (3) and (4).*

$$\stackrel{\approx}{A} = \int_{x \in X} \int_{u \in J_x} \frac{1}{(x,u)},\ J_x \subseteq [0,1] \tag{3}$$

$$\begin{gathered} \stackrel{\approx}{A} = \left(\stackrel{\sim}{A}^U, \stackrel{\sim}{A}^L \right) \\ = \left(a_1^U, a_2^U, a_3^U, a_4^U; H_1\left(\stackrel{\sim}{A}^U\right), H_2\left(\stackrel{\sim}{A}^U\right) \right) \left(a_1^L, a_2^L, a_3^L, a_4^L; H_1\left(\stackrel{\sim}{A}^L\right), H_2\left(\stackrel{\sim}{A}^L\right) \right) \end{gathered} \tag{4}$$

- $a_1^U, a_2^U, a_3^U, a_4^U, a_1^L, a_2^L, a_3^L, a_4^L$*—reference points of IT2F number* $\stackrel{\approx}{A}$,
- $H_j\left(\stackrel{\sim}{A}^U\right) \in [0,1]\ \ 1 \leq j \leq 2$*—value of* $a_{(j+1)}^U$ *in upper trapezoidal membership function.*
- $H_j\left(\stackrel{\sim}{A}^L\right) \in [0,1];\ 1 \leq j \leq 2$*—value of* $a_{(j+1)}^L$ *in lower trapezoidal membership function.*

which can graphically be interpreted as in Figure 2.

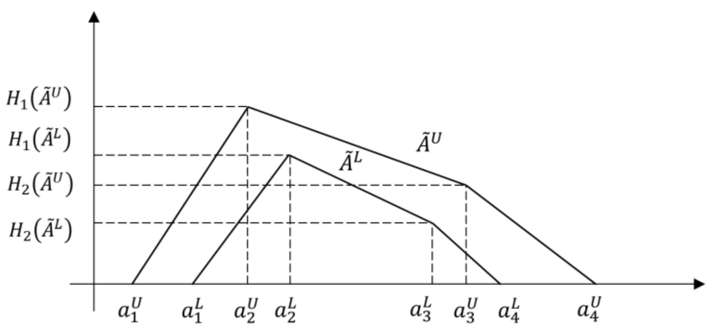

Figure 2. The IT2F number.

Let $\overset{\approx}{A}_1 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right)$ and $\overset{\approx}{A}_2 = \left(\tilde{A}_2^U, \tilde{A}_2^L\right)$ be two IT2F numbers, whose form is interpreted in Equation (4), then the arithmetic operations between them can be defined as follows:

Definition 3. *The addition operation between two IT2F numbers $\overset{\approx}{A}_1$ and $\overset{\approx}{A}_2$ is defined as in Equation (5)*

$$\overset{\approx}{A}_1 \oplus \overset{\approx}{A}_2 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \oplus \left(\tilde{A}_2^U, \tilde{A}_2^L\right) \\ = \left(\begin{matrix} a_{11}^U + a_{21}^U,\ a_{12}^U + a_{22}^U,\ a_{13}^U + a_{23}^U,\ a_{14}^U + a_{24}^U; \\ min\left(H_1\left(\tilde{A}_1^U\right), H_1\left(\tilde{A}_2^U\right)\right), min\left(H_2\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_2^U\right)\right) \end{matrix}\right), \left(\begin{matrix} a_{11}^L + a_{21}^L,\ a_{12}^L + a_{22}^L,\ a_{13}^L + a_{23}^L,\ a_{14}^L + a_{24}^L; \\ min\left(H_1\left(\tilde{A}_1^L\right), H_1\left(\tilde{A}_2^L\right)\right), min\left(H_2\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_2^L\right)\right) \end{matrix}\right) \tag{5}$$

Definition 4. *The Subtraction operation between two IT2F numbers $\overset{\approx}{A}_1$ and $\overset{\approx}{A}_2$ is defined as in Equation (6)*

$$\overset{\approx}{A}_1 \ominus \overset{\approx}{A}_2 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \ominus \left(\tilde{A}_2^U, \tilde{A}_2^L\right) \\ = \left(\begin{matrix} a_{11}^U - a_{21}^U,\ a_{12}^U - a_{22}^U,\ a_{13}^U - a_{23}^U,\ a_{14}^U - a_{24}^U; \\ min\left(H_1\left(\tilde{A}_1^U\right), H_1\left(\tilde{A}_2^U\right)\right), min\left(H_2\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_2^U\right)\right) \end{matrix}\right), \left(\begin{matrix} a_{11}^L - a_{21}^L,\ a_{12}^L - a_{22}^L,\ a_{13}^L - a_{23}^L,\ a_{14}^L - a_{24}^L; \\ min\left(H_1\left(\tilde{A}_1^L\right), H_1\left(\tilde{A}_2^L\right)\right), min\left(H_2\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_2^L\right)\right) \end{matrix}\right) \tag{6}$$

Definition 5. *The multiplication operation between two IT2F numbers $\overset{\approx}{A}_1$ and $\overset{\approx}{A}_2$ is defined as in Equation (7)*

$$\overset{\approx}{A}_1 \otimes \overset{\approx}{A}_2 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \otimes \left(\tilde{A}_2^U, \tilde{A}_2^L\right) \\ = \left(\begin{matrix} a_{11}^U \cdot a_{21}^U,\ a_{12}^U \cdot a_{22}^U,\ a_{13}^U \cdot a_{23}^U,\ a_{14}^U \cdot a_{24}^U; \\ min\left(H_1\left(\tilde{A}_1^U\right), H_1\left(\tilde{A}_2^U\right)\right), min\left(H_2\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_2^U\right)\right) \end{matrix}\right), \left(\begin{matrix} a_{11}^L \cdot a_{21}^L,\ a_{12}^L \cdot a_{22}^L,\ a_{13}^L \cdot a_{23}^L,\ a_{14}^L \cdot a_{24}^L; \\ min\left(H_1\left(\tilde{A}_1^L\right), H_1\left(\tilde{A}_2^L\right)\right), min\left(H_2\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_2^L\right)\right) \end{matrix}\right) \tag{7}$$

Definition 6. *The arithmetic operation between crisp value s and an IT2F number $\overset{\approx}{A}_1$ is defined as in Equation (8).*

$$s \otimes \overset{\approx}{A}_1 = s \otimes \left(\tilde{A}_1^U, \tilde{A}_1^L\right) = \left(\begin{matrix} \left(s \cdot a_{11}^U, s \cdot a_{12}^U, s \cdot a_{13}^U, s \cdot a_{14}^U; H_1\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_1^U\right)\right), \\ \left(s \cdot a_{11}^L, s \cdot a_{12}^L, s \cdot a_{13}^L, s \cdot a_{14}^L; H_1\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_1^L\right)\right) \end{matrix}\right) \tag{8}$$

Definition 7. *The reciprocal operation of an IT2F number $\overset{\approx}{A}_1$ is defined as in Equation (9).*

$$\left(\overset{\approx}{A}_1\right)^{-1} = \left(\left(\frac{1}{a_{14}^U}, \frac{1}{a_{13}^U}, \frac{1}{a_{12}^U}, \frac{1}{a_{11}^U}; H_1\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_1^U\right)\right)\left(\frac{1}{a_{14}^L}, \frac{1}{a_{13}^L}, \frac{1}{a_{12}^L}, \frac{1}{a_{11}^L}; H_1\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_1^L\right)\right)\right) \tag{9}$$

3.3. Interval Type-2 Delphi Model

The Delphi method is a formal communication strategy or approach originally conceived as a systematic interactive predictive process based on an expert panel [73]. Today, it is extensively used as part of hybrid MCDM models, to identify critical decision factors. The study employs the IT2FD-based approach for eliciting the most important evaluation criteria.

The synthesis of type-1 fuzzy set theory and conventional Delphi is often used as a part of the hybrid MCDM frameworks to resolve the ambiguity and vagueness of an expert's judgments, which are issues that the conventional Delphi approach has always suffered from. However, it can be noticed that the extensions of the Delphi method in the context of IT2F sets have not been taken much into consideration and is still in their infancy. There are only a few studies suggesting the application of an IT2FD-based approach, for instance; Shringi et al. [62] developed a hybrid IT2F Delphi-AHP model for analyzing critical factors for effective knowledge acquisition in construction safety training. Deveci et al. [74] introduced the IT2FD-based approach to rank indicators affecting site selection of vehicle shredding facilities. In study [75], the critical competencies for lifelong learning were assessed using the fuzzy model for sustainable education, whereby the IT2FD approach was employed to aggregate students' opinions into unique marks, during the assessment process. While Ayyildiz et al. [76] utilized IT2FD to determine the most important criteria that affect the credit evaluation process.

In order to provide a more intuitive and convenient way to address uncertain and ambiguous information during the Delphi process, the paper suggests an extension of the Delphi model in the context of IT2F sets. In this regard, the modified fuzzy Delphi model proposed by Gupta et al. [77] is used, in which IT2F sets are used instead of triangular type-1 fuzzy sets.

Since the experts $(E_k, k = 1, 2, \ldots, K)$, engaged in the Delphi process participate in different phases of the innovation process (IP) and have different experiences, qualifications, and designations, their judgments should be assigned different weights. For instance, the opinion of the expert with more experience, a higher designation, or more qualifications could be considered more trustworthy; therefore, the weight factors ($\tilde{\tilde{X}}_k$) will be assigned to the experts on this basis. The weight factor reflects the expert's competencies for dealing with the considered problem. The linguistic variables describing experts' experience, qualification, designation, and the phase of the innovation process (IP) they are involved in (which will be used as expert evaluation criteria in this study) can be quantified using IT2F numbers, according to Table 3. The weight factor for each expert is then formed as an aggregation of these variables and represents the arithmetic mean of the assigned IT2F numbers.

Table 3. IT2F scale for the expert evaluation criteria.

Experience	Qualification	Designation	IP Phase	Linguistic Variables	IT2F Numbers
≤5	Under graduate	Up to executive	Launch and market penetration	Low	(0, 0.1, 0.15, 0.3; 1, 1) (0.05, 0.1, 0.15, 0.2; 0.9, 0.9)
5–10	Graduate	Executive to Specialist	Idea generation	Medium	(0.3, 0.5, 0.55, 0.7; 1, 1) (0.4, 0.5, 0.55, 0.6; 0.9, 0.9)
10–15	Master graduation	Specialist to Manager	Concept development	High	(0.7, 0.85, 0.9, 1; 1, 1) (0.8, 0.85, 0.9, 0.95; 0.9, 0.9)
≥15	Post graduate	Manager to GM	Product development	Very high	(0.9, 1, 1, 1; 1, 1) (0.95, 1, 1, 1; 0.9, 0.9)

In the experts' opinions ($\tilde{\tilde{I}}_{jk}$) on the importance of considering each of the identified criteria ($C_j,\ j = 1, 2, \ldots, n$), an IT2F evaluation matrix is established:

$$\overset{\approx}{L} = \left(\overset{\approx}{l}_{jk}\right)_{nxK} = \begin{matrix} \\ \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} \begin{matrix} E_1 & E_2 & \cdots & E_K \\ \overset{\approx}{X}_1 & \overset{\approx}{X}_2 & \cdots & \overset{\approx}{X}_K \\ \end{matrix} \begin{bmatrix} \overset{\approx}{l}_{11} & \overset{\approx}{l}_{12} & \cdots & \overset{\approx}{l}_{1K} \\ \overset{\approx}{l}_{21} & \overset{\approx}{l}_{22} & \cdots & \overset{\approx}{l}_{2K} \\ \vdots & \vdots & & \vdots \\ \overset{\approx}{l}_{n1} & \overset{\approx}{l}_{n2} & \cdots & \overset{\approx}{l}_{nK} \end{bmatrix} \quad (10)$$

Those opinions are expressed according to the scale accounted for in Table 4.

Table 4. IT2F scale.

Linguistic Variables	IT2F Numbers
Very Low (VL)	(0, 0, 0, 0.01; 1, 1) (0, 0, 0, 0.05; 0.9, 0.9)
Low (L)	(0, 0.1, 0.15, 0.3; 1, 1) (0.05, 0.1, 0.15, 0.2; 0.9, 0.9)
Medium Low (ML)	(0.1, 0.3, 0.35, 0.5; 1, 1) (0.2, 0.3, 0.35, 0.4; 0.9, 0.9)
Medium (M)	(0.3, 0.5, 0.55, 0.7; 1, 1) (0.4, 0.5, 0.55, 0.6; 0.9, 0.9)
Medium High (MH)	(0.5, 0.7, 0.75, 0.9; 1, 1) (0.6, 0.7, 0.75, 0.8; 0.9, 0.9)
High (H)	(0.7, 0.85, 0.9, 1; 1, 1) (0.8, 0.85, 0.9, 0.95; 0.9, 0.9)
Very High (VH)	(0.9, 1, 1, 1; 1, 1) (0.95, 1, 1, 1; 0.9, 0.9)

According to Gupta et al. [77], the average weight for each criterion ($\overset{\approx}{w}_{\delta j}$) could be determined by Equation (11).

$$\overset{\approx}{w}_{\delta j} = \frac{\sum_{k=1}^{K} \overset{\approx}{X}_k \otimes \overset{\approx}{l}_{jk}}{K} \quad (11)$$

The defuzzification of IT2F weights in this study is performed by the Center of Area (COA) method, providing the Best Nonfuzzy Performance (BNP) value, as suggested in [78], the BNP value can be obtained as in Equation (12).

$$w_{\delta j} = \frac{\int xu(x)dx}{\int u(x)dx} = \frac{-w_{\delta j1} \cdot w_{\delta j2} + w_{\delta j3} \cdot w_{\delta j4} + \frac{1}{3}\left(w_{\delta j4} - w_{\delta j3}\right)^2 - \frac{1}{3}\left(w_{\delta j2} - w_{\delta j1}\right)^2}{-w_{\delta j1} - w_{\delta j2} + w_{\delta j3} + w_{\delta j4}} \quad (12)$$

where $w_{j1,2,3 \text{ and } 4}$ represents the arithmetic mean of the upper and lower boundaries of the IT2F weight ($\overset{\approx}{w}_{\delta j}$).

The computation of the criterion minimum acceptable weight ($\overset{\approx}{R}_{\delta j}$) is determined by Equation (13), where R_k stands for the minimum acceptable criterion weight denoted as a percentage expressed by the kth expert. This variable can be defuzzified by Equation (12). The criteria whose weights ($w_{\delta j}$) are lower than the estimated minimum acceptable weight ($R_{\delta j}$) are omitted from the further evaluation procedure.

$$\overset{\approx}{R}_{\delta j} = \frac{\sum_{k=1}^{K} \overset{\approx}{X}_k \otimes R_k}{K} \quad (13)$$

3.4. Interval Type-2 AHP Model

The Analytical Hierarchy Process (AHP) method is a method of hierarchical weight decision analysis introduced by Saaty [79]. Based upon the pairwise comparison of a set of objects, the AHP is performed so as to elicit a corresponding priority vector that indicates preferences. The synthesis of the fuzzy set and the AHP method has successfully been applied in modeling diverse engineering and management problems, such as renewable energy project portfolio optimization [80], optimal maintenance strategy selection [55], green supplier selection [56], resilient supplier selection [81], partner selection in collaborative technological R&D projects [25], and supplier selection in the era of Industry 4.0 [82].

The first step within the criteria weighting process based upon the IT2F AHP methodology implies the establishment of a pairwise comparison matrix ($\tilde{\tilde{A}} = \left(\tilde{\tilde{a}}_{yj}\right)_{n\times n}$) among all the criteria $\left(C_j, j = 1, 2, \ldots, n\right)$:

$$\tilde{\tilde{A}} = \left(\tilde{\tilde{a}}_{yj}\right)_{n\times n} = \begin{matrix} \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} \begin{matrix} \begin{matrix} C_1 & C_2 & \cdots & C_n \end{matrix} \\ \begin{bmatrix} 1 & \tilde{\tilde{a}}_{12} & \cdots & \tilde{\tilde{a}}_{1n} \\ \tilde{\tilde{a}}_{21} & 1 & \cdots & \tilde{\tilde{a}}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{\tilde{a}}_{n1} & \tilde{\tilde{a}}_{n2} & \cdots & 1 \end{bmatrix} \end{matrix} = \begin{bmatrix} 1 & \tilde{\tilde{a}}_{12} & \cdots & \tilde{\tilde{a}}_{1n} \\ \frac{1}{\tilde{\tilde{a}}_{12}} & 1 & \cdots & \tilde{\tilde{a}}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{\tilde{\tilde{a}}_{1n}} & \frac{1}{\tilde{\tilde{a}}_{2n}} & \cdots & 1 \end{bmatrix} \quad (14)$$

The matrix elements ($\tilde{\tilde{a}}_{yj}$) refer to the preference of the criterion y over the criterion j determined by the experts involved in the prioritization process. In the first phase, preferential relationships are expressed by means of linguistic statements. In the next phase, it is converted to IT2F numbers by mapping on an IT2F scale. The IT2F numbers representing the linguistic statements used in the criteria weighting process in this study are introduced in Table 5 and graphically presented in Figure 3.

Table 5. IT2F scale for criteria weighting process.

Linguistic Statements	IT2F Numbers
Absolutely Strong (AS)	(7, 8, 9, 9; 1, 1) (7.2, 8.2, 8.8, 9; 0.8, 0.8)
Very Strong (VS)	(5, 6, 8, 9; 1, 1) (5.2, 6.2, 7.8, 8.8; 0.8, 0.8)
Fairly Strong (FS)	(3, 4, 6, 7; 1, 1) (3.2, 4.2, 5.8, 6.8; 0.8, 0.8)
Slightly Strong (SS)	(1, 2, 4, 5; 1, 1) (1.2, 2.2, 3.8, 4.8; 0.8, 0.8)
Exactly Equal (EE)	(1, 1, 1, 1; 1, 1) (1, 1, 1, 1; 1, 1)

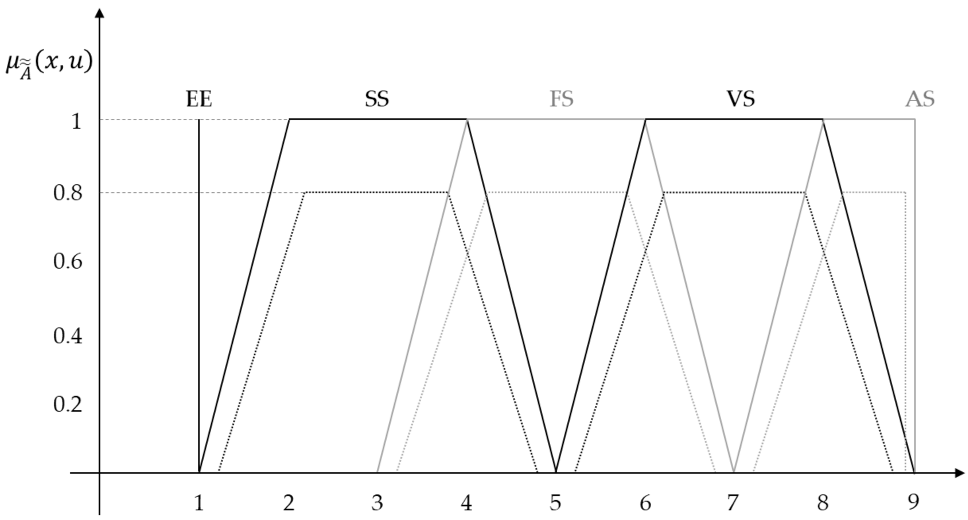

Figure 3. IT2F membership functions for linguistic statements used in criteria weighting process.

A consistency test is used to reveal the inconsistency within the established pairwise comparison matrix. In order to verify pairwise comparison matrix consistency, the consistency rate (CR) is introduced, and its value is obtained by Equation (15).

$$CR = \frac{CI}{RI} \quad (15)$$

where CI is a consistency index obtained by Equation (16)

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{16}$$

and λ_{max} is the largest eigenvalue of matrix $\tilde{\tilde{A}}$.

The RI is random index, and its value being dependent on the order of the matrix (see [79]).

If the $CR < 0.1$, then the pairwise comparison matrix is acceptable, otherwise, the matrix must be reformed.

If the criteria pairwise comparison is performed as a group process, then the individual pairwise comparison matrices can be aggregated using Equations (17) and (18), where $\tilde{\tilde{a}}^{k}_{yj}$ is the criteria preferential relation expressed by the kth expert.

$$\tilde{\tilde{a}}_{yj} = \left(\prod_{k=1}^{K} \tilde{\tilde{a}}^{k}_{yj}\right)^{\frac{1}{K}} = \left[\tilde{\tilde{a}}^{1}_{yj} \otimes \tilde{\tilde{a}}^{2}_{yj} \otimes \ldots \otimes \tilde{\tilde{a}}^{K}_{yj}\right]^{\frac{1}{K}} \tag{17}$$

$$\sqrt[K]{\tilde{\tilde{a}}^{k}_{yj}} = \begin{pmatrix} \sqrt[K]{a^{U}_{yj1}}, \sqrt[K]{a^{U}_{yj2}}, \sqrt[K]{a^{U}_{yj3}}, \sqrt[K]{a^{U}_{yj4}}; H^{U}_{1}(a_{yj}); H^{U}_{2}(a_{yj}), \\ \sqrt[K]{a^{L}_{yj1}}, \sqrt[K]{a^{L}_{yj2}}, \sqrt[K]{a^{L}_{yj3}}, \sqrt[K]{a^{L}_{yj4}}; H^{L}_{1}(a_{yj}); H^{L}_{2}(a_{yj}) \end{pmatrix} \tag{18}$$

There are several approaches to the generation of priorities from the pairwise comparison relations including the Least Squares (LS) method [83]; the geometric mean method [84]; the Logarithmic Least Squares (LLS) method [85]; the extent analysis method [86]; goal programming [87]; the Fuzzy Preference Programming (FPP) method [88]; the linear programming method [89]; the least deviation method [90]; the Weighted Least Square (WLS) and the quadratic programming methods [91].

A modification of the Buckley [84] fuzzy AHP model will be applied to generate criteria weights from the pairwise comparison matrix, whereby the modified model uses IT2F sets instead of the trapezoidal type-1 fuzzy set as it is more accurate in uncertainty modeling, due to the membership function, which is fuzzy by itself. This includes the generation of the fuzzy geometric mean ($\tilde{\tilde{r}}_{y}$) for each matrix row using the geometric mean technique as follows:

$$\tilde{\tilde{r}}_{y} = \left(\prod_{y=1}^{n} \tilde{\tilde{a}}_{yj}\right)^{\frac{1}{n}} = \left[\tilde{\tilde{a}}_{y1} \otimes \tilde{\tilde{a}}_{y2} \otimes \ldots \otimes \tilde{\tilde{a}}_{yn}\right]^{\frac{1}{n}} \tag{19}$$

The IT2F weights ($\tilde{\tilde{w}}_{j}$) are obtained by the fuzzy geometric mean ($\tilde{\tilde{r}}_{y}$) as follows:

$$\tilde{\tilde{w}}_{j} = \tilde{\tilde{r}}_{y} \otimes \left[\tilde{\tilde{r}}_{1} \oplus \ldots \oplus \tilde{\tilde{r}}_{y} \oplus \ldots \tilde{\tilde{r}}_{n}\right]^{-1} \tag{20}$$

The non-fuzzy weights of C_j are obtained in the same manner as in Equation (12).

3.5. Interval Type-2 PROMETHEE Model

The Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) [92] is a widely used outranking method that enables aggregation of the alternative evaluations established based on multiple, often conflicting criteria. The paper proposes using the extension of the PROMETHEE method in the context of the IT2F set. The majority of so-far-used IT2F MCDM models could be characterized as scoring or compromising models, whereas the extended outranking methods have not been thoroughly investigated. A literature review reveals only a few studies using the PROMETHEE method in the IT2F environment. For instance, Chen [93] established the PROMETHEE model that used signed distance-based generalized criteria and comprehensive preference indices in the IT2F set environment, while Wu et al. [66] used the IT2F PROMETHEE model to develop an investment decision-making framework. This model was also used as a part of the two-stage DM framework for the inland nuclear power plant site selection in synthesis with the GIS Wu et al. [94].

Let define the MCDM problem of m alternatives $(Z_i, i = 1, 2, \ldots, m)$ and n evaluation criteria $(C_j,\ j = 1, 2, \ldots, n)$. The fuzzy evaluation matrix is then defined as in Equation (21). The alternative performance $(\overset{\approx}{f}_{ij})$ is expressed using the scale provided in Table 4.

$$\overset{\approx}{F} = \left(\overset{\approx}{f}_{ij}\right)_{mxn} = \begin{matrix} \\ Z_1 \\ Z_2 \\ \vdots \\ Z_m \end{matrix} \begin{matrix} C_1 & C_2 & \cdots & C_n \\ \left[\begin{matrix} \overset{\approx}{f}_{11} & \overset{\approx}{f}_{12} & \cdots & \overset{\approx}{f}_{1n} \\ \overset{\approx}{f}_{21} & \overset{\approx}{f}_{22} & \cdots & \overset{\approx}{f}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \overset{\approx}{f}_{m1} & \overset{\approx}{f}_{n1} & \cdots & \overset{\approx}{f}_{mn} \end{matrix}\right] \end{matrix} \tag{21}$$

$$\overset{\approx}{f}_{ij} = \left(\tilde{F}_{ij}^{\;U}, \tilde{F}_{ij}^{\;L}\right) = \left(f^U_{ij1}, f^U_{ij2}, f^U_{ij3}, f^U_{ij4}; H_1\left(\tilde{F}^U_{ij}\right), H_2\left(\tilde{F}^U_{ij}\right)\right)\left(f^L_{ij1}, f^L_{ij2}, f^L_{ij3}, f^L_{ij4}; H_1\left(\tilde{F}^L_{ij}\right), H_2\left(\tilde{F}^L_{ij}\right)\right) \tag{22}$$

In the next step, a normalized fuzzy evaluation matrix ($\overset{\approx}{D} = \left(\overset{\approx}{d}_{ij}\right)_{mxn}$) is established.

$$\overset{\approx}{d}_{ij} = \left(\tilde{D}_{ij}^{\;U}, \tilde{D}_{ij}^{\;L}\right) = \begin{cases} \left(\frac{f^U_{ij1}}{f^L_{max\ j}}, \frac{f^U_{ij2}}{f^L_{max\ j}}, \frac{f^U_{ij3}}{f^L_{max\ j}}, \frac{f^U_{ij4}}{f^L_{max\ j}}\right), \left(\frac{f^L_{ij1}}{f^L_{max\ j}}, \frac{f^L_{ij2}}{f^L_{max\ j}}, \frac{f^L_{ij3}}{f^L_{max\ j}}, \frac{f^L_{ij4}}{b^L_{max\ j}}\right), & if\ C_j \in C_I \\ \left(\frac{f^L_{min\ j}}{f^U_{ij4}}, \frac{f^L_{min\ j}}{f^U_{ij3}}, \frac{f^L_{min\ j}}{f^U_{ij2}}, \frac{f^L_{min\ j}}{f^U_{ij1}}\right), \left(\frac{f^L_{min\ j}}{f^L_{ij4}}, \frac{f^L_{min\ j}}{f^L_{ij3}}, \frac{f^L_{min\ j}}{f^L_{ij2}}, \frac{f^L_{min\ j}}{f^L_{ij1}}\right), & if\ C_j \in C_{II} \end{cases} \tag{23}$$

$$\begin{matrix} f^L_{max\ j} = max\left\{f^L_{ij} | i = 1, 2, \cdots, m\right\} \\ f^L_{min\ j} = min\left\{f^L_{ij} | i = 1, 2, \cdots, m\right\} \end{matrix} \quad C_I\ and\ C_{II}$$

C_I applies to benefit criteria and C_{II} to cost criteria.

The alternatives' outranking relations can be expressed by the preference function:

$$\overset{\approx}{P}_j(z_i, z_g) = \overset{\approx}{P}_j\left(\overset{\approx}{D}_{ij} - \overset{\approx}{D}_{gj}\right) \tag{24}$$

It is a non-falling function characterized as: $0 \le \overset{\approx}{P}_j(z_i, z_g) \le 1$ and $\overset{\approx}{P}_j(z_i, z_g) \neq \overset{\approx}{P}_j(z_g, z_i)$, therewith it acquiring the value 0 for $\overset{\approx}{D}_{ij} - \overset{\approx}{D}_{gj} < 0$. The preference function expresses the intensity of the preference of the alternative z_i over z_g, concerning the criterion C_j, which can be interpreted as:

- $\overset{\approx}{P}_j(z_i, z_g) = 0$—indifference—$\overset{\approx}{D}_{ij} = \overset{\approx}{D}_{gj}$
- $\overset{\approx}{P}_j(z_i, z_g) \sim 0$—weak preference—$\overset{\approx}{D}_{ij} > \overset{\approx}{D}_{gj}$
- $\overset{\approx}{P}_j(z_i, z_g) \sim 1$—strong preference—$\overset{\approx}{D}_{ij} >> \overset{\approx}{D}_{gj}$
- $\overset{\approx}{P}_j(z_i, z_g) = 1$—strict preference—$\overset{\approx}{D}_{ij} >>> \overset{\approx}{D}_{gj}$

The PROMETHEE method enables each decision criterion to be assigned a specific type of preference function by its characteristics, as well as the associated parameters that represent the intensity, limits, and speed of preference. The six different types of preference functions (Equations (25)–(30)) suggested by Brans and Vincke [92] can be used to express preferences in the majority of real-world problems.

Usual Criterion

$$\widetilde{\widetilde{P}}_j(z_i, z_g) = \begin{cases} 0, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} \leq 0 \\ 1, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} > 0 \end{cases} \tag{25}$$

U-shape Criterion

$$\widetilde{\widetilde{P}}_j(z_i, z_g) = \begin{cases} 0, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} \leq \widetilde{\widetilde{q}} \\ 1, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} > \widetilde{\widetilde{q}} \end{cases} \tag{26}$$

V-shape Criterion

$$\widetilde{\widetilde{P}}_j(z_i, z_g) = \begin{cases} 0, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} \leq 0 \\ \left(\widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj}\right)/\widetilde{\widetilde{p}}, & 0 < \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} \leq \widetilde{\widetilde{p}} \\ 1, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} > \widetilde{\widetilde{p}} \end{cases} \tag{27}$$

Level Criterion

$$\widetilde{\widetilde{P}}_j(z_i, z_g) = \begin{cases} 0, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} \leq \widetilde{\widetilde{q}} \\ 1/2, & \widetilde{\widetilde{q}} < \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} \leq \widetilde{\widetilde{p}} \\ 1, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} > \widetilde{\widetilde{p}} \end{cases} \tag{28}$$

V-shape with indifference Criterion

$$\widetilde{\widetilde{P}}_j(z_i, z_g) = \begin{cases} 0, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} \leq \widetilde{\widetilde{q}} \\ \left(\left(\widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj}\right) - \widetilde{\widetilde{q}}\right)/\left(\widetilde{\widetilde{p}} - \widetilde{\widetilde{q}}\right), & \widetilde{\widetilde{q}} < \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} \leq \widetilde{\widetilde{p}} \\ 1, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} > \widetilde{\widetilde{p}} \end{cases} \tag{29}$$

Gaussian Criterion

$$\widetilde{\widetilde{P}}_j(z_i, z_g) = \begin{cases} 0, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} \leq 0 \\ 1 - e^{-\left(\widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj}\right)^2/2\widetilde{\widetilde{\delta}}^2}, & \widetilde{\widetilde{D}}_{ij} - \widetilde{\widetilde{D}}_{gj} > 0 \end{cases} \tag{30}$$

where:

$$e^{\widetilde{\widetilde{A}}} = \left(e^{a_1^U}, e^{a_2^U}, e^{a_3^U}, e^{a_4^U}; H_1\left(\widetilde{A}^U\right), H_2\left(\widetilde{A}^U\right)\right), \left(e^{a_1^L}, e^{a_2^L}, e^{a_3^L}, e^{a_4^L}; H_1\left(\widetilde{A}^L\right), H_2\left(\widetilde{A}^L\right)\right) \tag{31}$$

In order to obtain the final alternatives rank, it is necessary to determine the preference index $\pi(z_i, z_g)$ which reflects the overall preference of the alternative z_i over the z_g concerning all the evaluation criteria, where $\widetilde{\widetilde{w}}_j$ is the relative weight of criterion C_j:

$$\pi(z_i, z_g) = \sum_{j=1}^{n} \widetilde{\widetilde{w}}_j \cdot \widetilde{\widetilde{P}}_j(z_i, z_g) \tag{32}$$

The exploitation of the obtained preferential relations to establish the rank of the alternatives includes the calculation of outgoing flows ($\varnothing^+(z_i)$) by Equation (33) and incoming flows ($\varnothing^-(z_i)$) using the Equation (34)—for partial ranking, and net flows ($\varnothing(z_i)$) by Equation (35)—for establishing the final rank of the alternative.

$$\varnothing^+(z_i) = \frac{1}{n-1}\sum_{z_x \in Z}^{n-1} \pi(z_i, z_x) \tag{33}$$

$$\varnothing^-(z_i) = \frac{1}{n-1}\sum_{z_x \in Z}^{n-1} \pi(z_x, z_i) \tag{34}$$

$$\varnothing(z_i) = \varnothing^+(z_i) - \varnothing^-(z_i) \tag{35}$$

4. Results

The case study has been conducted to verify the applicability and demonstrate the feasibility of the proposed hybrid IT2F MCDM model. The five-phase MCDM hybrid process has been conducted in accordance with the above-presented methodological framework (Figure 1). In this context, five alternative partners are identified to be evaluated. The decision-making process engaged a group of four experts: two university professors in the field of Engineering Management and two experts with experience in managing the OI projects.

4.1. Establishing the Evaluation Criteria List by IT2FD

At the first step, IT2F logic is used to assign weight factors ($\overset{\approx}{X}_k$) to experts involved in the Delphi process (E_k). The experts' qualifications, experience designation, and IP phase they are involved in are used as evaluation criteria. This Delphi process included four experts, one from each of the following IP phases: idea generation, concept development, product development, and launch and market penetration phases.

The linguistic variables that describe these experts' experience, qualification, designation, and IP phase (given in Table 6) are quantified using IT2F numbers in accordance with Table 3. The arithmetic mean of the IT2F numbers assigned to the expert on this basis is used to determine its weight factor. The results are shown in Table 6.

Table 6. The experts' relative weights.

Expert	Experience	Qualification	Designation	IP Phase	IT2F Experts Weights ($\overset{\approx}{X}_k$)
E_1	3	Master graduate	Specialist to Manager	Idea generation	(0.43, 0.58, 0.63, 0.75; 1, 1) (0.51, 0.58, 0.63, 0.68; 0.9, 0.9)
E_2	8	Postgraduate	Manager to GM	Product development	(0.75, 0.88, 0.89, 0.93; 1, 1) (0.81, 0.88, 0.89, 0.9; 0.9, 0.9)
E_3	15	Graduate	Specialist to Manager	Concept Development	(0.65, 0.8, 0.84, 0.93; 1, 1) (0.74, 0.8, 0.84, 0.88; 0.9, 0.9)
E_4	9	Graduate	Executive to Specialist	Launch and market penetration	(0.33, 0.49, 0.54, 0.68; 1, 1) (0.41, 0.49, 0.54, 0.59; 0.9, 0.9)

Each expert is asked through the questionnaire to evaluate the importance of each potential criterion from the list established in Section 3 (Table 2) by using the corresponding IT2F numbers. Those opinions are expressed according to the scale accounted for in Table 4, which resulted in an evaluation matrix (Table 7). The average criteria weights are generated from the established evaluation matrix, considering the experts' relative weights according to Equation (11). Along with the criteria filtering threshold, the minimum acceptable weight for each criterion is decided. The initial criteria are analyzed with regard to this threshold. According to the findings (Table 7), ten criteria are accepted, while the others are rejected since their significance weights are below the threshold.

Table 7. The results of the criteria evaluation.

Criteria	Aggregate Criteria Weight ($\tilde{\tilde{w}}_{\delta j}$)	Aggregate MAW ($\tilde{\tilde{R}}_{\delta j}$)	Criteria Weight	MAW	Selected Criteria
Technological innovation level	(0.46, 0.66, 0.71, 0.82; 1, 1) (0.57, 0.66, 0.71, 0.75; 0.9, 0.9)	(0.48, 0.61, 0.64, 0.73; 1, 1) (0.55, 0.61, 0.64, 0.67; 0.9, 0.9)	0.663	0.612	✓
Technological complementarity	(0.38, 0.58, 0.65, 0.82; 1, 1) (0.5, 0.58, 0.65, 0.72; 0.9, 0.9)	(0.43, 0.56, 0.59, 0.67; 1, 1) (0.5, 0.56, 0.59, 0.62; 0.9, 0.9)	0.608	0.561	✓
Product experience	(0.19, 0.39, 0.45, 0.64; 1, 1) (0.29, 0.39, 0.45, 0.52; 0.9, 0.9)	(0.33, 0.43, 0.45, 0.51; 1, 1) (0.38, 0.43, 0.45, 0.47; 0.9, 0.9)	0.416	0.430	
Number of patents held	(0.34, 0.54, 0.61, 0.78; 1, 1) (0.45, 0.54, 0.61, 0.67; 0.9, 0.9)	(0.39, 0.5, 0.53, 0.6; 1, 1) (0.45, 0.5, 0.53, 0.56; 0.9, 0.9)	0.566	0.507	✓
Expected capabilities of abstraction	(0.09, 0.26, 0.31, 0.48; 1, 1) (0.17, 0.26, 0.31, 0.37; 0.9, 0.9)	(0.26, 0.32, 0.34, 0.39; 1, 1) (0.29, 0.32, 0.34, 0.36; 0.9, 0.9)	0.280	0.327	
Technology transfer capability	(0.45, 0.65, 0.7, 0.82; 1, 1) (0.56, 0.65, 0.7, 0.75; 0.9, 0.9)	(0.47, 0.59, 0.63, 0.71; 1, 1) (0.54, 0.59, 0.63, 0.66; 0.9, 0.9)	0.655	0.601	✓
Overlapping knowledge base	(0.11, 0.27, 0.33, 0.49; 1, 1) (0.19, 0.27, 0.33, 0.38; 0.9, 0.9)	(0.26, 0.33, 0.35, 0.39; 1, 1) (0.3, 0.33, 0.35, 0.37; 0.9, 0.9)	0.295	0.333	
Product-specific knowledge	(0.4, 0.6, 0.67, 0.82; 1, 1) (0.51, 0.6, 0.67, 0.73; 0.9, 0.9)	(0.44, 0.56, 0.59, 0.67; 1, 1) (0.5, 0.56, 0.59, 0.62; 0.9, 0.9)	0.623	0.565	✓
Market knowledge complementarity	(0.27, 0.47, 0.53, 0.71; 1, 1) (0.38, 0.47, 0.53, 0.6; 0.9, 0.9)	(0.38, 0.49, 0.51, 0.58; 1, 1) (0.44, 0.49, 0.51, 0.54; 0.9, 0.9)	0.495	0.491	✓
Expected knowledge maturity	(0.22, 0.41, 0.47, 0.66; 1, 1) (0.31, 0.41, 0.47, 0.53; 0.9, 0.9)	(0.34, 0.43, 0.45, 0.52; 1, 1) (0.39, 0.43, 0.45, 0.48; 0.9, 0.9)	0.436	0.442	
Past experiences	(0.2, 0.39, 0.44, 0.62; 1, 1) (0.29, 0.39, 0.44, 0.5; 0.9, 0.9)	(0.35, 0.45, 0.47, 0.53; 1, 1) (0.4, 0.45, 0.47, 0.50; 0.9, 0.9)	0.408	0.451	
Financial assets	(0.06, 0.19, 0.24, 0.40; 1, 1) (0.12, 0.19, 0.24, 0.29; 0.9, 0.9)	(0.2, 0.26, 0.27, 0.31; 1, 1) (0.23, 0.26, 0.27, 0.29; 0.9, 0.9)	0.216	0.260	
Expected debt ratio and refund ability	(0.32, 0.52, 0.57, 0.72; 1, 1) (0.42, 0.52, 0.57, 0.62; 0.9, 0.9)	(0.39, 0.5, 0.53, 0.60; 1, 1) (0.45, 0.5, 0.53, 0.55; 0.9, 0.9)	0.528	0.503	✓
Financial resources demand of the project	(0.09, 0.26, 0.31, 0.48; 1, 1) (0.17, 0.26, 0.31, 0.37; 0.9, 0.9)	(0.23, 0.29, 0.31, 0.35; 1, 1) (0.27, 0.29, 0.31, 0.33; 0.9, 0.9)	0.280	0.297	
Return of investment	(0.16, 0.34, 0.4, 0.58; 1, 1) (0.25, 0.34, 0.4, 0.46; 0.9, 0.9)	(0.28, 0.36, 0.38, 0.44; 1, 1) (0.33, 0.36, 0.38, 0.41; 0.9, 0.9)	0.365	0.368	
Collaborative behavior	(0.43,0.62,0.67,0.80;1,1) (0.53,0.62,0.67,0.72;0.9,0.9)	(0.46,0.58,0.61,0.7;1,1) (0.53,0.58,0.61,0.65;0.9,0.9)	0.629	0.588	✓
Mutual trust and commitment	(0.21, 0.41, 0.47, 0.65; 1, 1) (0.31, 0.41, 0.47, 0.53; 0.9, 0.9)	(0.35, 0.44, 0.46, 0.52; 1, 1) (0.4, 0.44, 0.46, 0.49; 0.9, 0.9)	0.429	0.444	
Management and organizational culture	(0.24, 0.44, 0.5, 0.69; 1, 1) (0.33, 0.44, 0.5, 0.56; 0.9, 0.9)	(0.35, 0.45, 0.47, 0.54; 1, 1) (0.41, 0.45, 0.47, 0.5; 0.9, 0.9)	0.461	0.454	✓
Previous relationship	(0.03, 0.14, 0.18, 0.33; 1, 1) (0.08, 0.14, 0.18, 0.23; 0.9, 0.9)	(0.18, 0.23, 0.24, 0.27; 1, 1) (0.21, 0.23, 0.24, 0.25; 0.9, 0.9)	0.163	0.230	
Propensity to change	(0.04, 0.15, 0.19, 0.34; 1, 1) (0.09, 0.15, 0.19, 0.24; 0.9, 0.9)	(0.2, 0.24, 0.26, 0.29; 1, 1) (0.22, 0.24, 0.26, 0.27; 0.9, 0.9)	0.175	0.246	
Geographical proximity	(0.02, 0.11, 0.15, 0.29; 1, 1) (0.06, 0.11, 0.15, 0.20; 0.9, 0.9)	(0.17, 0.21, 0.23, 0.26; 1, 1) (0.19, 0.21, 0.23, 0.24; 0.9, 0.9)	0.136	0.218	
Symmetry of scale and scope	(0, 0.06, 0.09, 0.21; 1, 1) (0.03, 0.06, 0.09, 0.13; 0.9, 0.9)	(0.16, 0.2, 0.21, 0.23; 1, 1) (0.18, 0.2, 0.21, 0.22; 0.9, 0.9)	0.084	0.197	
Compatibility of corporation strategies	(0.18, 0.37, 0.43, 0.61; 1, 1) (0.27, 0.37, 0.43, 0.49; 0.9, 0.9)	(0.31, 0.4, 0.42, 0.48; 1, 1) (0.36, 0.4, 0.42, 0.44; 0.9, 0.9)	0.390	0.401	

Table 7. *Cont.*

Criteria	Aggregate Criteria Weight ($\tilde{\tilde{w}}_{\delta j}$)	Aggregate MAW ($\tilde{\tilde{R}}_{\delta j}$)	Criteria Weight	MAW	Selected Criteria
Convergence of expectations between partners	(0.36, 0.56, 0.63, 0.80; 1, 1) (0.47, 0.56, 0.63, 0.70; 0.9, 0.9)	(0.41, 0.53, 0.56, 0.64; 1, 1) (0.48, 0.53, 0.56, 0.59; 0.9, 0.9)	0.585	0.539	
Motivation and goal correspondence	(0.22, 0.41, 0.47, 0.66; 1, 1) (0.31, 0.41, 0.47, 0.53; 0.9, 0.9)	(0.33, 0.42, 0.44, 0.5; 1, 1) (0.38, 0.42, 0.44, 0.47; 0.9, 0.9)	0.436	0.446	
Strategic objectives of intellectual property management	(0.16,0.35,0.41,0.60;1,1) (0.25,0.35,0.41,0.47;0.9,0.9)	(0.31, 0.39, 0.41, 0.47; 1, 1) (0.35, 0.39, 0.41, 0.44; 0.9, 0.9)	0.375	0.395	
Market complementarity	(0.09, 0.25, 0.29, 0.46; 1, 1) (0.16, 0.25, 0.29, 0.35; 0.9, 0.9)	(0.23, 0.29, 0.31, 0.35; 1, 1) (0.26, 0.29, 0.31, 0.33; 0.9, 0.9)	0.265	0.295	

The IT2FD process results reinforce the significance of specific factors related to the partners' technological competencies, such as Technological innovation level, Technological complementarity, Number of patents held, and Technology transfer capability, highlighting the increasing technological complexity or necessity of technology fusion to innovate. In terms of the resource complementarity dimension, the evaluation process will incorporate Product-specific knowledge and Market knowledge complementarity criteria, with less emphasis on evaluating the financial terms of the corporation and strategic alignment.

4.2. Criteria Weighting by the IT2F AHP

The fuzzified linguistic variables defined in the previous section (Table 5) are now applied to describe the preference relations between the criteria considered by each expert. This has resulted in individual pairwise comparison matrices whose consistencies have been clarified and confirmed. Based on the established matrices and Equation (16) we can obtain CI: $CI_1 = 0.077, CI_2 = 0.087, CI_3 = 0.107, CI_4 = 0.106$; $RI = 1.49$, for $n = 10$. According to Equation (15) CR is obtained: $CR_1 = 0.0514\%$, $CR_2 = 0.0587\%$, $CR_3 = 0.0721\%$, $CR_4 = 0.0708\%$. Since $CR_{1,2,3,4} < 0.1$, established pairwise comparison matrices could be considered to be consistent.

The IT2F aggregated pairwise matrix is obtained by applying Equations (17) and (18). To generate criteria weights from these relations, the geometric mean is computed by Equation (19). Equation (20) is employed so as to establish IT2F criteria weights, and the composite criteria weights are available after defuzzifying by Equation (12) and normalizing.

The results (Table 8) emphasize that the criteria from the technological competencies dimension, specifically the technological innovation level (0.249) and the technology transfer capability (0.237), as well as the collaborative behavior criterion (0.14) as a represent of the cooperative capability dimension, are the most significant evaluation criteria according to the nature of the company's OI processes, the contextual conditions, and the innovation strategy at the corporate level.

Table 8. The results of the criteria weighting.

Criteria		IT2F Criteria Geometric Means ($\tilde{\tilde{r}}_y$)	IT2F Criteria Weight ($\tilde{\tilde{w}}_j$)	Non-Fuzzy Normalized Weights (w_j)
C_1	Technological innovation level	(1.081, 2.353, 6.755, 11.827; 1, 1) (1.308, 2.657, 6.114, 10.414; 0.8, 0.8)	(0.238, 0.245, 0.253, 0.256; 1, 1) (0.24, 0.246, 0.253, 0.256; 0.8, 0.8)	0.249
C_2	Technological complementarity	(0.471, 0.856, 2.12, 3.755; 1, 1) (0.544, 0.943, 1.929, 3.275; 1, 1)	(0.104, 0.089, 0.079, 0.081; 1, 1) (0.1, 0.087, 0.08, 0.08; 1, 1)	0.088
C_3	Number of patents held	(0.258, 0.475, 1.399, 2.974; 1, 1) (0.297, 0.529, 1.241, 2.476; 0.8, 0.8)	(0.057, 0.049, 0.052, 0.064; 1, 1) (0.054, 0.049, 0.051, 0.061; 0.8, 0.8)	0.056

Table 8. *Cont.*

	Criteria	IT2F Criteria Geometric Means ($\tilde{\tilde{r}}_y$)	IT2F Criteria Weight ($\tilde{\tilde{w}}_j$)	Non-Fuzzy Normalized Weights (w_j)
C_4	Technology transfer capability	(0.995, 2.439, 6.777, 10.263; 1, 1) (1.251, 2.778, 6.226, 9.43; 0.8, 0.8)	(0.219, 0.254, 0.254, 0.222; 1, 1) (0.23, 0.257, 0.257, 0.231; 0.8, 0.8)	0.237
C_5	Product-specific knowledge base	(0.409, 0.85, 2.476, 4.616; 1, 1) (0.488, 0.956, 2.225, 3.995; 0.8, 0.8)	(0.09, 0.088, 0.093, 0.1; 1, 1) (0.089, 0.088, 0.092, 0.098; 0.8, 0.8)	0.093
C_6	Market knowledge complementarity	(0.135, 0.224, 0.626, 1.397; 1, 1) (0.151, 0.246, 0.554, 1.144; 0.8, 0.8)	(0.03, 0.023, 0.023, 0.03; 1, 1) (0.028, 0.023, 0.023, 0.028; 0.8, 0.8)	0.027
C_7	Expected debt ratio and refund ability	(0.098, 0.161, 0.459, 1.061; 1, 1) (0.109, 0.177, 0.404, 0.860; 0.8, 0.8)	(0.022, 0.017, 0.017, 0.023; 1, 1) (0.02, 0.016, 0.017, 0.021; 0.8, 0.8)	0.020
C_8	Collaborative behavior	(0.69, 1.404, 3.591, 5.825; 1, 1) (0.822, 1.567, 3.286, 5.227; 0.8, 0.8)	(0.152, 0.146, 0.135, 0.126; 1, 1) (0.151, 0.145, 0.136, 0.128; 0.8, 0.8)	0.140
C_9	Management and organizational culture	(0.048, 0.074, 0.222, 0.571; 1, 1) (0.052, 0.081, 0.193, 0.450; 0.8, 0.8)	(0.011, 0.008, 0.008, 0.012; 1, 1) (0.01, 0.007, 0.008, 0.011; 0.8, 0.8)	0.010
C_{10}	Convergence of expectations between partners	(0.353, 0.774, 2.254, 3.94; 1, 1) (0.428, 0.874, 2.036, 3.48; 0.8, 0.8)	(0.078, 0.08, 0.084, 0.085; 1, 1) (0.078, 0.081, 0.084, 0.085; 0.8, 0.8)	0.082

4.3. OI Partner Evaluation by IT2F PROMETHEE

The expert group has established a list of all potential OI partners, and after the initial screening, a total of five alternatives remained to be evaluated further. The experts reached a consistent evaluation of alternatives for each criterion based on the objective assessment of personalized knowledge and experience specific to a criterion using fuzzified linguistic terms. Those options are expressed according to the scale accounted in Table 4. As a result, the evaluation matrix was formed (Table 9). The matrix is normalized according to Equation (23).

Table 9. The IT2F evaluation matrix.

	Criteria	Alternative					Preference Function Type	Parameters	
		Z_1	Z_2	Z_3	Z_4	Z_5		p	q
C_1	Technological innovation level	L	MH	M	ML	MH	U-shape	-	-
C_2	Technological complementarity	M	VH	H	H	MH	V-shape	L	
C_3	Number of patents held	L	MH	ML	VL	M	V-shape	L	
C_4	Technology transfer capability	L	H	MH	M	ML	U-shape	L	
C_5	Product-specific knowledge base	H	MH	M	M	ML	V-shape	L	
C_6	Market knowledge complementarity	VH	VL	ML	H	L	V-shape with indifference	L	M
C_7	Expected debt ratio and refund ability	MH	ML	VL	ML	L	V-shape	ML	
C_8	Collaborative behavior	VH	L	M	H	MH	V-shape	ML	
C_9	Management and organizational culture	H	ML	MH	H	M	V-shape with indifference	VL	ML
C_{10}	Convergence of expectations between partners	ML	M	MH	MH	VL	V-shape with indifference	VL	ML

The preference functions for each criterion and the corresponding parameters according to the criteria characteristics are selected (Table 9). The level of technological innovation has a direct impact on the OI process's innovation performance; thus, the higher assessments strictly prefer their lower counterparts. It also proves to be the most important issue in OI partner selection for this company; therefore, the Usual Criterion type is designated for this criterion. The criteria C_2, C_3, C_4, C_5, C_7, and C_8 are considered superior only if the differences in the assessments reach a certain level. Before this level is reached, the higher level is linearly superior to the lower. It works for the criteria C_6, C_9, and C_{10} similarly, except for the fact that the difference cannot be made until the difference in the assessments has reached a certain level. Therefore, the corresponding preference function is designated as the V-shape with indifference Criterion. When it comes to criterion C_4, no difference can be made until the difference in the assessments reaches a certain level; thus, the U-shape Criterion is selected.

The preference index for each pair of alternatives, the outgoing flow, the incoming flow, and the net flow of each alternative OI partner are computed by Equations (33)–(35). For an easy ranking, the net flows are ultimately defuzzified by Equation (12). According to the calculation results presented in Table 10, the recommended ranking of the alternatives is: $Z_2 \rightarrow Z_3 \rightarrow Z_4 \rightarrow Z_5 \rightarrow Z_1$, so the alternative Z_2 is recommended to company as a compromise solution.

Table 10. The outgoing flow, the incoming flow, the net flow and the final ranking.

	Outgoing Flow ($\varnothing^+(z_i)$)	**Incoming Flow ($\varnothing^-(z_i)$)**	**Net Flow ($\varnothing(z_i)$)**	**Non-Fuzzy Net Flow**	**Rank**
Z_1	(0.141, 0.128, 0.119, 0.096; 1, 1) (0.140, 0.127, 0.118, 0.114; 0.8, 0.8)	(0.294, 0.302, 0.303, 0.260; 1, 1) (0.297, 0.303, 0.304, 0.270; 0.8, 0.8)	(−0.153, −0.174, −0.184, −0.164; 1, 1) (−0.158, −0.176, −0.185, −0.156; 0.8, 0.8)	−0.1700	5
Z_2	(0.3, 0.304, 0.271, 0.215; 1, 1) (0.302, 0.305, 0.271, 0.262; 0.8, 0.8)	(0.11, 0.099, 0.094, 0.077; 1, 1) (0.108, 0.099, 0.094, 0.088; 0.8, 0.8)	(0.191, 0.205, 0.177, 0.138; 1, 1) (0.194, 0.206, 0.177, 0.174; 0.8, 0.8)	0.1824	1
Z_3	(0.219, 0.224, 0.223, 0.172; 1, 1) (0.221, 0.224, 0.224, 0.189; 0.8, 0.8)	(0.188, 0.179, 0.146, 0.122; 1, 1) (0.188, 0.178, 0.145, 0.143)	(0.031, 0.045, 0.078, 0.05; 1, 1) (0.034, 0.046, 0.079, 0.046; 0.8, 0.8)	0.0523	2
Z_4	(0.203, 0.191, 0.187, 0.132; 1, 1) (0.203, 0.191, 0.187, 0.152; 0.8, 0.8)	(0.2, 0.2, 0.197, 0.133; 1, 1) (0.202, 0.2, 0.197, 0.165; 0.8, 0.8)	(0.003, −0.008, −0.01, −0.001; 1, 1) (0.001, −0.009, −0.009, −0.013; 0.8, 0.8)	−0.0050	3
Z_5	(0.169, 0.165, 0.164, 0.132; 1, 1) (0.170, 0.165, 0.164, 0.137; 0.8, 0.8)	(0.241, 0.232, 0.225, 0.156; 1, 1) (0.24, 0.232, 0.225, 0.188; 0.8, 0.8)	(−0.072, −0.067, −0.061, −0.024; 1, 1) (−0.07, −0.067, −0.062, −0.051; 0.8, 0.8)	−0.0581	4

5. Discussion

Selecting suitable partners capable of operationally and strategically contributing to the OI project goals is a strategic decision for companies striving to successfully transform the OI strategy into a sustainable competitive advantage.

Despite the extensive research on OI partner selection, there is still a notable research gap regarding establishing a comprehensive set of OI partner performance indicators. A comprehensive framework consisting of five critical dimensions (technological competencies, resource complementarity, financial terms of collaboration, cooperative capability, and strategic alignments), and twenty-seven indicators of OI partner performance has been developed in this study, which provides a holistic approach to OI partner selection, ensuring that the most critical technological, operational, and strategic aspects of OI partner evaluation were captured. This leads to a more integrated and coherent list of potential OI partner evaluation criteria.

In addition, this study aims to propose a hybrid MCDM methodology framework integrating Delphi, AHP, and PROMETHEE methods. In order to reflect the uncertainty, inherent to the decision-making process, in the best way, the theory of IT2F sets is employed. The proposed hybrid MCDM model represents a certain methodological advancement in identifying and evaluating OI partner performance indicators. The IT2F Delphi method enables the inclusion of expert subjective judgments, enabling a more comprehensive and inclusive approach to the identification of the most essential evaluation criteria. This results in a contingent and reliable set of OI partner performance indicators, enhancing the accuracy and practicality of the chosen evaluation criteria depending on the nature of the company's innovation processes as well as the contextual conditions and the corporate innovation strategy. The combination of IT2F AHP and IT2F PROMETHEE methods used in this paper yielded a more precise multi-criteria evaluation of the alternatives, under a high uncertainty level. Its main merits can be concluded from the following perspectives: criteria properties are treated in a proper way; it is suitable for solving complex decision-making problems when there are significant differences in participants' perceptions of the decision-making process; it has the ability to express preferences in a way similar to the human way of thinking; and it provides a mathematically simple synthesis of the obtained results for deriving criteria weights. In addition, the proposed approach is apt to incorporate imprecise data into the analysis using IT2F set theory. Namely, the classical MCDM methods that consider deterministic or random processes cannot effectively address OI partner selection problems due to their inherent fuzziness and imprecision. Hence, an IT2F MCDM algorithm is presented here to rectify the problem of vagueness and uncertainty in a more realistic way.

Furthermore, the study has some managerial implications. Based on the study findings, managers can establish specific management strategies, policies, and best practices to maximize the synergy of collaboration in OI projects in a systematic manner.

The proposed approach is illustrated through a case study of a high-tech company, to show the validity of the decision-making process. The study's results highlight the significance of specific factors related to the partners' technological competencies, such as Technological innovation level, Technological complementarity, Number of patents held, and Technology transfer capability, while the evaluation process will be less focused on the evaluation of financial terms of cooperation and strategic alignment. Based on the multi-criteria evaluation process, alternative Z_2 is selected as a compromise solution. We firmly believe that the underlying concept of this approach is both rational and comprehensible. The proposed hybrid IT2F MCDM model can be generalized and applied to other complex decision-making problems in the domains of engineering and management that encounter imprecise, indefinite, and subjective data or vague information.

The main limitations of the methodology presented in the paper are: (i) the decision-makers subjective assessments, which may influence the accuracy of the input data; (ii) the AHP method disregards potential dependences between evaluation criteria.

Future research can include the following: (i) employing methods that evaluate the interrelationships between the criteria, such as the Analytic Network Process (ANP) or DEMATEL; (ii) using other tools that accept uncertainty in decision-making, in particular, the proposed MCDM methods can be combined with other types of fuzzy sets for method extension to solve uncertainty in OI partner selection problems; and (iii) developing a comparative framework encompassing various MCDM methods that might highlight the optimal methods for selecting an OI partner.

Author Contributions: Conceptualization, S.P., J.V.V., D.D.M. and V.P.; methodology, S.P., J.V.V. and D.D.M.; validation, S.P., J.V.V. and D.D.M.; formal analysis, S.P., J.V.V., D.D.M. and V.P.; investigation, S.P., J.V.V. and D.D.M.; Data curation, S.P., J.V.V. and V.P.; Writing—original draft, S.P., J.V.V., D.D.M. and V.P.; writing—review & editing, J.V.V. and D.D.M.; visualization, S.P., J.V.V. and V.P.; supervision, J.V.V. and D.D.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, under Grant 451-03-47/2023-01/200132 with University of Kragujevac—Faculty of Technical Sciences Čačak.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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