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Leading the green charge: A novel type-2 fuzzy VIKOR method applied to eco-conscious freight transport

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ABSTRACT

Imprecise and ambiguous information is critical in multi-criteria group decision-making (MCGDM) problems. Quantification of such information is essential in determining the best alternative. In this study, an interval type-2 fuzzy set (IT2FS) possibility-based Vlsekriterijumska Optimizacija i Kompromisno Resenje (VIKOR) approach is developed to address MCGDM problems. The possibilities of IT2FSs are employed to establish a new decision matrix containing crisp information, which decreases the computational complexities involved with processing IT2FSs. With the use of the new decision matrix, decision-makers (DMs) may now assess alternatives in pairs to determine which alternatives have benefits over the others. Due to the adoption of possibilities of IT2FSs, the proposed approach works efficiently even in cases where the differences between alternatives are minor. Since road freight transport emissions represent a very significant contributor to transportation-related greenhouse gas emissions, there is an urgent need to seek sustainable solutions in this area. Thus, the model is applied to the road freight transport to rank different fuel alternatives. The proposed possibility-based VIKOR method provides a robust framework for evaluating renewable fuel alternatives by considering sustainability benefits and market barriers, while overcoming several key limitations of traditional MCDM methods. It is recommended that this approach be utilized in real-world decision-making for sustainable freight transport planning. Future research could explore its integration with dynamic data sources for more adaptive and real-time decision support.

1. Introduction

The technique known as "multi-criteria decision making" (MCDM) provides a scientific and quantitative approach to decision-making problems that take into account several criteria and viewpoints (Ecer & Pamucar, 2022; Yadav et al., 2023). In order to solve real-world problems that have been recognized in a range of academic subfields, several alternative multi-attribute decision making (MADM) techniques have been developed over the course of the previous few decades (Büyüközkan & Güler, 2021; Erol et al., 2022; Hendiani & Walther, 2025; Pamucar et al., 2018; Patel et al., 2023; Sarkar et al., 2023; Stević et al., 2020; Tang, Gu, et al., 2023). Many businesses have converted from asking a single decision maker (DM) to consulting a group of experts for decision making under multiple criteria, which is known as multi-attribute group decision making (MAGDM), in order to get more accurate results.

For the multi-criteria planning of complex systems, the systems with a lot of criteria and decision alternatives, the VIKOR approach was developed in 1998 as one of the early MCDM techniques (S Opricovic, 1998). This approach focuses on rating and choosing from a range of potential options when there are competing criteria by putting forth a workable compromise. The VIKOR approach and the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) (Alkan & Kahraman, 2023; Haktanır & Kahraman, 2024; Hendiani & Walther, 2023b; Lin et al., 2023; Otay et al., 2024) are widely contrasted, despite the fact that each employs a unique aggregation function and normalizing technique. The optimum point from the TOPSIS perspective should be located the furthest from the negative ideal solution and the closest to the positive ideal solution. Consequently, it is appropriate for a cautious DM who would choose to make a choice that maximizes profit while minimizing risks (Awasthi & Kannan, 2016; Qi et al., 2021; Tao & Jiang, 2021). The VIKOR technique, on the other hand, is appropriate for circumstances in which the objective is to maximize profit while the risk

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Nomenclature

MCDM	Multi-Criteria Decision-Making
MADM	Multi-Attribute Decision-Making
MAGDM	Multi-Attribute Group Decision-Making
VIKOR	Vlsekriterijumska Optimizacija i Kompromisno Resenje
TOPSIS	Technique for Order Performance by Similarity to Ideal Solution
IT2FS	Interval Type-2 Fuzzy Set
ÍT2FBM	Interval Type-2 Fuzzy Bonferroni Mean

Parameters & Greek letters

$\tilde{\tilde{\psi}}$	Interval type-2 fuzzy number
A_i	Alternative i
c_j	Criterion j
$L^-\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right)$	Lower possibility of $\tilde{\tilde{\psi}}$ being larger than $\tilde{\tilde{\phi}}$
$L^+\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right)$	Upper possibility of $\tilde{\tilde{\psi}}$ being larger than $\tilde{\tilde{\phi}}$
$L\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right)$	Overall possibility of $\tilde{\tilde{\psi}}$ being larger than $\tilde{\tilde{\phi}}$
$P_{\tilde{\tilde{\psi}}_{ij}}$	Likelihood-based performance index
Y	Likelihood-based decision matrix
$P^+{}_{\tilde{\tilde{\psi}}}$	Best ideal vector
$P^-{}_{\tilde{\tilde{\psi}}}$	Worst ideal vector
S_i	Utility measure
R_i	Regret measure
$d\left(\tilde{\tilde{\psi}}, \tilde{\tilde{\phi}}\right)$	Distance between $\tilde{\tilde{\psi}}$ and $\tilde{\tilde{\phi}}$
χ_i	Ranking measure
w_j	Weight of criterion j
λ	Weight of strategy

associated with the choice is viewed as being of less significance (Alhadidi & Alomari, 2024; Hendiani & Walther, 2024; Serafim Opricovic & Tzeng, 2007; Tu et al., 2021). The main benefit of the VIKOR technique is that it allows for the trade-off between the opposition's least amount of individual regret and the majority's highest group utility (Kim & Ahn, 2019).

Fuzzy sets are a fundamental tool in the process of making decisions, usually while solving problems that feature properties such as uncertainty and vagueness. The so-called type-1 fuzzy set (T1FSs) commonly adopts a crisp membership function to map each element to a value between 0 and 1 characterizing the degree of membership. Although they are efficient in many applications, the membership values in T1FSs are crisp, though they originate from intrinsically imprecise linguistic terms such as "high," "low," or "moderate." This may be considered too simplistic to model real-world application problems, for which DMs usually express their evaluations using ambiguous or subjective terms. To eliminate this weakness, interval type-2 fuzzy sets (IT2FSs) extend the T1FS by adding another layer of uncertainty. Unlike T1FSs, where each element has only one single value of membership, IT2FSs assign to each element an interval of membership values. This interval reflects the uncertainty about the exact degree of membership. IT2FSs are particularly suitable for situations when linguistic assessments are too vague or incoherent. For instance, terms such as "high" would be mapped to a single crisp value by T1FSs, whereas IT2FSs map "high" to a range of possible values. In other words, IT2FSs are more complex and flexible in modeling the opinion of experts. IT2FSs present certain advantages over T1FSs. Firstly, IT2FSs offer more sophistication in the modeling of uncertainty, capturing better the imprecision of linguistic evaluations. This becomes very helpful in real-world decision-making problems where different experts may imply different meanings for certain qualitative terms. Secondly, the use of IT2FSs introduces more robustness in dealing with linguistic evaluations because they allow capturing variability and possible disagreement among experts regarding the meaning of certain terms. That is, one expert may understand "moderate" differently than another. IT2FSs allow the expression of such discrepancies using intervals rather than forcing an agreement on one value. There are also comparisons between IT2FSs and type-1 fuzzy sets in practice. Bai & Wang (2018) extended their prior work on type-1 fuzzy logic controller for an laser tracking system and further showed that interval type-2 fuzzy logic controller outperforms type-1 fuzzy logic controller in such applications. The laser tracking system regulates the angles and velocities of a two-degree-of-freedom gimbals system to track a moving target, and high tracking accuracy, smooth operation, and robustness against random noise are expected. Extensive simulations in this paper have shown that interval type-2 fuzzy logic controllers are able to provide better tracking accuracy, speed of response, and robustness to noise due to their power in handling uncertainties via the footprint of uncertainty compared with type-1 fuzzy logic controllers. interval type-2 fuzzy logic controllers provide smoother control with fewer oscillations and lower steady-state errors and, hence, are more suitable for high-performance applications requiring precision and stability. Orooji et al. (2019) investigated the purpose, application, architecture, and evaluation method of medical systems by analyzing 12 related articles between 2007 and 2017. The findings indicate that type-2 fuzzy logic-based systems outperform other type-1 and machine learning approaches regarding diagnostic accuracy, precision, and robustness to noise. Type-2 fuzzy logic handles uncertainty and ambiguity better, thus suiting those medical domains where a decision is needed to be taken in uncertain conditions. Almaraashi (2024) proposed a practical design of the type-2 fuzzy logic systems for global horizontal irradiance forecast over the Kingdom of Saudi Arabia. Indeed, the introduction of the type-2 fuzzy logic systems enhances robustness against uncertainties introduced by the inputs compared with type-1 fuzzy logic systems. Its major disadvantage is the higher computational cost. A new four-stage design embodies strengths of both systems and further improves computational cost about 93.7 %, while retaining superior predictive accuracy of type-2 fuzzy logic systems. Results also showed that type-2 fuzzy logic systems are stronger in handling uncertainty compared to type-1 fuzzy logic systems and can therefore perform better in making forecasts under a complex and uncertainty-rich environment. Tang et al. (2023) proposed an R-mathematical programming method for multi-attribute group decision making (MAGDM) using R-sets and prospect theory under bounded rationality. A new approach computed prospect values, defined consistency indices, and optimized weights via a state transition algorithm. In Tang et al. (2025) they also proposed an R-mathematical programming method for risk-based MAGDM, integrating R-sets, regret theory, the Banzhaf function, and LINMAP to address attribute interactions and bounded rationality. They defined R-utility and R-regret functions to compute Banzhaf R-perceived utility, introduced consistency indices, and formulated a bi-objective model to optimize weights and identify the R-ideal solution. Solved via NSGA-II, the model generated a non-dominated set, with four decision-making schemes selecting the best trade-off solution.

Kim & Ahn (2019) proposed a novel VIKOR approach that substitutes incomplete criteria weights for traditional weighing techniques like analytical hierarchy process (AHP) or analytical network process (ANP) for subjective weights. In order to solve the challenge of selecting green suppliers for manufacturing, Wu et al. (2019) suggested an integrated technique employing interval type-2 fuzzy sets for combining the best-worst method with the VIKOR technique. The T-Spherical fuzzy (T-SF)

VIKOR approach for compromise ranking in multiple criteria analysis was introduced by Chen (2022). It proposed an analytical framework based on an evolved T-SF scoring function and a Minkowski-type T-SF distance measure to overcome the difficulties in addressing T-Spherical fuzziness. Raj Mishra et al. (2022) generalized the VIKOR approach with Fermatean hesitant fuzzy sets (FHFSs) to provide a unique MADM approach. A remoteness index-based FHF-VIKOR technique was introduced along with distance measurements for FHFSs in the suggested approach. The maximum deviation principle and generalized distance measure were used to weight attributes. Tian et al. (2021) offered an expanded VIKOR approach under a picture fuzzy environment sustainability evaluation framework for water environment treatment public–private partnership projects. The framework comprises a thorough indexing mechanism and a new fuzzy similarity-based technique. The new risk-based fuzzy VIKOR (R-VIKOR) technique was presented by Mousavi et al. (2021) to manage the risk associated with new product development (NPD) initiatives in creative manufacturing companies. The R-numbers approach is used in the methodology to assess fuzzy risk data. Using interpretative structural modeling, risk variables are categorized and rated. In order to improve interval type-2 fuzzy MADM, Qin et al. (2015) developed a modification of the VIKOR approach utilizing prospect theory. They provided an innovative measure of distance for interval type-2 fuzzy sets and suggested a decision-making framework. To evaluate Chinese manufacturing businesses' sustainability enterprise risk management criteria, Cheng et al. (2021) presented the VIKOR-q-ROFSs technique. It uses fuzzy q-rung orthopair numbers (q-ROFNs) and a fuzzy q-rung orthopair fuzzy weighted averaging operator (q-ROFWAO) for decision-making. Liu et al. (2020) used linguistic D-numbers (L-DNs) to expand the VIKOR approach to tackle MADM problems with unknown attribute weights. They also provided a new combination rule and enhanced the notion of fuzzy entropy for LDNs. The created LD-VIKOR technique gives a practical strategy for making decisions with LDNs in the face of ambiguity. The VIKOR approach is extended by Riaz and Tehrim (2021) to provide a unique multi-attribute group decision-making method based on bipolar fuzzy sets (BFS). The notion of data measurement is improved by incorporating connection numbers (CNs) and creating metrics for BFS. Zhou and Chen (2021) extended the VIKOR approach for multi-criteria decision-making using Pythagorean fuzzy sets (PF). They introduced a new generalized distance measurement for PF sets and incorporated risk preference of DMs. Wei et al. (2020) introduced the use of the VIKOR approach for 2-tuple linguistic neutrosophic numbers (2TLNNs) to solve multiple criterion group decision making. The approach was expanded to handle interval-valued 2-tuple linguistic neutrosophic numbers (IV2TLNNs) and considered competing criteria. Erouglu and Sahin (2020) proposed an extended neutrosophic VIKOR method with a new score function and distance measure, demonstrating its effectiveness in renewable energy alternative selection and offering potential applications in various soft computing problems.

Despite all the novelties and efficiencies that previous methods brought into the state-of-the-art literature for the VIKOR approach, there are remaining gaps that need further attention: 1) Complexity of fuzzy processes: Designing fuzzy membership functions, selecting fuzzy numbers and linguistic terms, and aggregating fuzzy information all increase the complexity of fuzzy processing in VIKOR. Large-scale problems necessitate careful analysis combined with effective algorithms since complexity rises with the number of alternatives, criteria, and linguistic phrases. 2) Dominance relations: In the approach of the VIKOR method, fuzzy processing means ranking the alternatives according to their fuzzy assessments. Very often the fuzzy numbers representing alternatives have to be compared by means of dominance relations in fuzzy sets. The ambiguity and imprecision can make dominance relationships difficult to obtain and hence the overall rankings since imprecise comparisons and inferences are involved, particularly with more sophisticated fuzzy types, such as interval type-2 fuzzy sets. 3) Dependence to normalization approach: One of the drawbacks is a strong dependence of VIKOR on the normalization procedure. Before analysis, VIKOR requires that the criteria values first be normalized to a common scale. However, this step of normalization can be arbitrary and dependent on the method of normalization used. Different methods of normalization lead to different rankings and judgments, hence affecting the results. In order to overcome the aforementioned disadvantages, we will introduce a new possibility-based VIKOR method which is developed based on a new decision matrix established by possibilities of IT2FSs preference relations.

Eco-friendly freight transport is an area where much useful research is urgently needed, with the sector currently making such a huge contribution to GHG emissions and being inextricably linked with global sustainability goals. For instance, road freight transport alone comprised 73.2 % of the EU's GHG emissions in transportation in 2022 (EEA, 2024), indicating how urgent such a need really is to determine feasible solutions. This basically means that renewable fuels lie at the heart of every decarbonization strategy, but the optimal alternative must be chosen for with the consideration of a number of often conflicting sustainability-related and market barrier criteria. The complexity of the above decision-making problems requires advanced decision-making tools that are able to handle uncertainty, linguistic vagueness, and trade-offs among the criteria, which the proposed IT2FS-based VIKOR method does.

A number of benefits are produced by applying the proposed method to eco-conscious freight transport problems. First, the IT2FS-based VIKOR method considers the inherent uncertainty of expert judgments when expressing views related to both sustainability criteria and market barriers. For instance, experts might make use of such vague terms as "very high" to describe the performance of fuels, which the method does accommodate, representing linguistic evaluations as ranges that capture assessment ambiguity. In this respect, one will get a closer look at more realistic and nuanced analyses of renewable fuel alternatives, which enhances the reliability of rankings. The proposed method does not require normalization-one of the common steps in traditional MCDM approaches that can introduce biases and distort the rankings. This ensures that the results are robust and directly reflective of the criteria values as assessed by the experts.

The complexity of eco-friendly freight transport calls for the meeting of particular demands, which hardly the available MCDM techniques could address effectively. For example, the traditional methods of VIKOR and TOPSIS make use of crisp data and normalization, that are generally inappropriate to imprecise and subjective evaluations, which is pretty common in such sustainability assessment issues. Also, most of them do not clearly distinguish between positive criteria-economic benefit, emission reduction-and negative criteria-public acceptance and infrastructure barriers-which may result in incomplete and/or biased evaluations. The proposed method overcomes these limitations by integrating positive and negative criteria into a decision matrix to make a holistic assessment of opportunities and challenges associated with each fuel alternative.

The key contributions in this study are: 1) According to new decision matrix, which is generalized with possibility degrees of IT2FSs, new kind of VIKOR is proposed, where computational complexity of treatment of IT2FSs for implementation of steps of VIKOR is removed. 2) A new pairwise comparison of alternatives is also provided that enables DMs to view the strengths and weaknesses of one alternative with respect to the others. 3) The proposed possibility-based VIKOR also avoids data normalization along the entire process since, for the input, it takes IT2FSs linguistic information from experts and converts it into possibilities of IT2FSs for the decision matrix. Therefore, the ranking that it yields is unique and robust. 4) Application to an illustrative example, which analyzes both barriers to market development and sustainability criteria as positive and negative criteria for renewable fuel alternatives, respectively, provides validity of the approach for practical use.

The theoretical basis for the changes in the proposed method of VIKOR is the intrinsic shortcoming that is present in the conventional

MCDM methods. Greater decision-making under high uncertainty can be achieved by using IT2FS and by avoiding normalization. Traditional VIKOR methods are widely applied but mostly depend on the normalization step, which can introduce a potential bias, especially when the criteria are scaled too far apart or are of a subjective preference nature. In our approach, the removal of this step serves dual theoretical purpose: IT2FS possibility-based preference relations for derivation of more unbiased and accurate reflection of DM judgments. This yields a decision matrix operating with crisp values deduced from the fuzzy possibilities, and hence a computation that is easier to perform and yet still encapsulates these nuanced preferences brought in by IT2FSs.

Besides that, the features of our approach are theoretically novel. It treats and reveals minor differences among alternatives not so highlighted by traditional VIKOR or even other MCDM methods such as TOPSIS. The classical TOPSIS works by calculating the distance of every alternative from an ideal solution with gains maximized and losses minimized. TOPSIS, while effective in many cases, tends to be less sensitive when there is a closeness in the performance of alternatives due to its deficiency of linear aggregation of distances. The proposed VIKOR model, that uses IT2FSs and avoids normalization, offers a further layer of sensitivity through its operation of pairwise comparisons of alternatives. This will make our model especially powerful for ranking alternatives with small differentiation, hence providing DMs with a more sensitive decision-making tool in choosing between closely competitive options. It is essential to outline the computational and functional benefits of the proposed model concerning conventional VIKOR. For example, while the traditional method of VIKOR operates on the principle that each criterion should be brought to a common unit scale, our modified approach avoids this requirement through the use of the possibility associated with IT2FSs. We can therefore model linguistic and qualitative information in a more accurate way with reduced subjective bias that is normally introduced through normalization. The main implication of this is that IT2FS approaches are particularly well-suited when, as in the case of the assessment of sustainability, many criteria exist and are frequently interconnected; traditional scaling can distort the true importance of each criterion. This approach also better suits the needs for real-world decision-making with improved interpretability and reduced computational overheads, especially for those applications where data is uncertain, imprecise, or qualitative.

However, this is a method with some disadvantages, as well. The new model reduces the total computational burden because it avoids the normalization process, but includes computational intensity with regard to the processing of IT2FS possibilities, which, for big decision-making scenarios, may be computationally demanding. This added complexity is recognized as a trade-off for higher accuracy in ranking and manipulation of uncertainty but may need higher computation for larger data sets. However, by removing the normalization biases, our method gains more robustness and adaptability; yet, it may introduce other layers of computation for obtaining the possibilities for IT2FSs, which might not be doable at every decision-making platform. In any case, further studies will aim to give a simplified version of these calculations or explore other fuzzy sets extensions, such as spherical or neutrosophic sets, which may allow further computational advantages.

The remainder of this research is organized as follows: Section 2 presents the literature analysis regarding the concepts that are used in this study. In Section 3, the proposed possibility-based VIKOR is presented step by step. In Section 4, the proposed approach is validated through comparative analysis and the efficacy and dominance of the proposed approach is proved. Section 4 also proves its applicability for renewable fuel alternatives by implementing different steps of the proposed approach. Section 5 investigates the results with sensitivity analysis and pairwise comparison. Section 6 presents the conclusions and final remarks of the study.

2. Literature review

2.1. Interval type-2 fuzzy sets and MCDM

Interval type-2 fuzzy sets (IT2FSs) are one of the generalizations for traditional type-1 fuzzy sets which are more precise in handling the ambiguity and subjectivity in human decision-making. These kinds of sets have been widely used in different topics especially within the context of MCDM during the past years. Celik et al. (2015) did a review article in which they summarized works for 82 studies on IT2FSs-based MCDM approaches, which are more capable of modeling uncertainty than traditional fuzzy sets. The reviewed papers, categorized into 35 single and hybrid approaches, outline their applications, results, and limitations. A statistical analysis has been used to depict the trend in IT2FS-based MCDM, thus enabling the researcher to understand the current state and future research directions in this area. Mohamadghasemi et al. (2020) addressed the problem of material handling equipment selection as a MCGDM issue and introduced Gaussian interval type-2 fuzzy sets (GIT2FSs) for weighting and evaluation of the criteria in a more refined way. By applying GIT2FSs, the paper used fuzzy weighted average for the aggregation of ratings and weights, and further extended ELECTRE III for ranking alternatives to determine the optimal equipment. Hendiani et al. (2020) proposed a new MCDM model for the selection of sustainable suppliers, considering interval type-2 trapezoidal fuzzy sets, representing uncertainty and subjective evaluations. The model adopts the possibility of interval type-2 fuzzy preference relations, integrating the triple bottom line criteria on sustainability from the literature and sets a benchmark framework upon which suppliers will be evaluated. Tang et al. (2022) proposed an IT2F programming method for risky MCDM with heterogeneous criteria and bounded rationality. Using 2-additive fuzzy measures and regret theory, they computed Banzhaf-based utility values and defined consistency and inconsistency indices. An optimization model was then proposed minimizing inconsistency while ensuring consistency constraints. Experimental results on investment selection confirm its effectiveness in handling risky MCDM problems. Nemati (2024) proposed a model for the selection of suppliers in a sustainable and resilient supply chain based on IT2FSs, which can better address uncertainties. The model integrates the newest version of the MULTIMOORA method, with criteria importance determined by the best-worst method and expert weights established via the modified MABAC approach.

Dorfeshan et al. (2023) proposed the model for integrating supply chain and project management decisions in the project-driven supply chains. The model considered supplier resilience assessment with a multi-part approach using criteria weighting via the extended best-worst method and expert weighting via a modified CODAS method based on average and positive ideal concepts. For dealing with uncertainty, IT2FSs were used. The critical path method related calculations have also defined a new subtraction operation that prevents negative values along with the criticality score of the project activities. A case study with regard to the construction of a hospital showed how the model managed delay and supplier resilience effectively. Meniz (2021) proposed a fuzzy metric function for IT2FSs, enhancing the TOPSIS method by maintaining the fuzzy structure in the process and applying defuzzification only in the final ranking step. A new partial order relation is proposed for IT2FSs. The advanced TOPSIS method is applied to the solution of the selection problem of a video chat program and gives an improved way of solving fuzzy decision problems. Chiao (2021) developed two new aggregation models of quantifier-guided ordered weighted averaging and Bonferroni mean operators with IT2FSs for the problems of interrelated MCDM. The developed models capture the interdependencies among the criteria and uncertainty using linguistic weights and ratings of the alternatives. It represents major contributions in the development of different extended aggregation models, constructs mixed-integer linear programming for optimal weights, and introduces the new paradigm-the interrelation-based MCDM. In the study presented by Mutlu et al. (2024), a novel risk assessment method was presented to the mining sector by overcoming some of the drawbacks of traditional methods using Pythagorean fuzzy AHP and IT2FSs. This study investigated the risk factors in Turkish Coal Enterprises. Meanwhile, the causes of non-fatal accidents have been divided into 25 sub-criteria under six main criteria. Goldani et al. (2023) proposed a new MCGDM methodology in an interval type-2 trapezoidal fuzzy environment for complex decision problems, including several points of view from experts. It provides three steps: the computation of criteria weights and consistency index and ratio calculation in the initial step within the IT2FSs cognitive best-worst method, optimizes the final computation of IT2TrF weights through an optimization model, and prioritizes the alternatives based on the likelihood-based method; the latter approach will be applied and justified with a problem of healthcare waste treatment technology selection during COVID-19.

Li et al. (2024) proposed a constrained interval type-2 fuzzy multi-criteria acceptability analysis approach to represent uncertainty in decision-making problems using constrained interval type-2 fuzzy sets. CIT2 fuzzy multi-criteria acceptability analysis models the uncertainty in decisions as regions of type-1 fuzzy assessments that are manipulated using type-1 operations. The originalities of this work concern the definition of the CIT2 fuzzy rank acceptability indexes, the determination of a weighted average of CIT2 fuzzy numbers, and the sampling-based algorithm for ranking and making decisions. The approach proposed by Jana et al. (2023) presents an improved IT2FVIKOR method, which improves some limitations of the traditional VIKOR approach. The conventional VIKOR fails to select those alternatives that could be superior for most of the criteria but lower for one of the criteria. The improved IT2FVIKOR provides more continuous and logical index values and yields better and more consistent rankings for MCDM problems.

2.2. Application of MCDM in transportation

Lots of studies have recently utilized MCDM for addressing problems of transportation and sustainability. The study presented by Shabani et al. (2022) investigates customer satisfaction in the use of public transport in Tehran during the COVID-19 pandemic, which has caused problems of low demand and contamination. It develops a hybrid model through BWM and fuzzy TOPSIS for determining the key evaluation criteria; relevant literature, Delphi method, and panel discussions were conducted; and a sample size of 392 was surveyed. It thus sets up a framework that identifies how policymakers could make improvements in services considering an integrated set of criteria, some of which pertain to the infection risks. To the best of the authors' knowledge, this is the first application of an integrated BWM and fuzzy TOPSIS model for the assessment of public transportation systems in light of a pandemic. The study presented by Dadashzadeh et al. (2024) proposes a three-step framework that is going to be used for assessing mobility as a service (MaaS) systems with a focus on the viewpoint of vulnerable social groups in terms of accessibility and inclusiveness. The prioritization of the key criteria for an inclusive MaaS system, by applying a MCDM method, was carried out through a survey of 105 transportation experts. It was found that accessible transport services, MaaS platforms, and data collection have the following percentage contribution: 51 %, 29 %, and 20 %, respectively. Concretely, the paper provides a real case in Portsmouth, UK, demonstrating how to use the framework and develops policy recommendations that could help guide stakeholders toward accessible and socially sustainable MaaS implementations.

Celik et al. (2013) introduced a new model to assess customer satisfaction in view of Istanbul's public transportation faced with a growing population. Satisfaction has been assessed in respect of four major public transportation services by combining survey data and using both statistical analysis and the fuzzy MCDM method. Passenger questionnaire and expert data were analyzed using fuzzy logic and Grey Relational Analysis (GRA) in order to solve intertwined criteria. It is a model incorporating GRA, TOPSIS, and Type-2 fuzzy sets, and so the assessment is closer to reality in strength in adapting to uncertainty. Bakioglu (2024) developed a framework for prioritizing sustainable transportation strategies on university campuses, considering both environmental and health impacts while fostering a culture of sustainability. Using a novel hybrid MCDM method by combining SWARA and EDAS with Picture fuzzy sets, the research identifies 8 main strategies, evaluated across 6 criteria with 23 sub-strategies. Results indicate that short-term action plans, such as bike facilities and parking reorganization, are ranked high because of feasibility and low cost, whereas long-term action plans that require substantial investment-such as flexible work policies and on-campus affordable housing-fall toward the bottom. In the study presented by Nassereddine & Eskandari (2017), satisfaction with public transportation is evaluated by a MCDM model in combination with Delphi methodology, group AHP, and PROMETHEE. Such an integrated method allowed realistic assessment to be made and could provide recommendations on improvements related to quality.

Samanta & Jana (2019) addressed two crucial issues in the realm of transportation decision-making using trapezoidal interval type-2 fuzzy numbers to deal with such ambiguity: first, proposing a method for transportation mode selection among different alternatives by ranking them according to decision-makers' preference based on a possibility degree matrix, and second, applying the chosen mode to a multi-item transportation problem by developing this problem into a single-objective problem using methods of fuzzy goal programming and convex combination. A generalized reduced gradient method was employed in order to solve the resulting model by LINGO-14.0. A new fuzzy MCGDM approach was presented by Kundu et al. (2017), which ranks interval type-2 fuzzy variables for better decision making. Using the ranking method based on relative preference index with generalized credibility measure, the study ranks the alternatives by representing linguistic ratings and criteria weights with interval type-2 fuzzy variables. Its application on a transportation mode selection problem provided the most suitable mode in view of the specified criteria. the study provided by Wang et al. (2022) evaluates the sustainability of the road transportation system in Organization for Economic Cooperation and Development (OECD) countries by using an MCDM model with an integrated entropy-CoCoSo approach. The entropy method assigns objective weights to criteria, while the CoCoSo method is used for ranking countries for their sustainability performance. It highlights the leading positions due to advanced infrastructure in Japan, Germany, and France, while Iceland, the United States, and Latvia rank at the bottom. Ghoushchi et al. (2023) focused on transportation greenhouse gas emissions through the use of an MCDM approach with spherical fuzzy set (SFS) to evaluate sustainable vehicle options in Tehran. In the study, the SWARA and MARCOS methods were combined in SFS and used to evaluate the vehicles that consider the criteria identified by the experts. Among the results, it has been identified that environmental impact is the most relevant criterion, while autonomous vehicles rank as the most sustainable option for reducing emissions.

2.3. Renewable fuels and MCDM

Heo et al. (2012) provided the evaluation of six hydrogen production methods using a fuzzy AHP, which was based on the concepts of benefits, opportunities, costs, and risks. Twelve evaluation factors were weighted and analyzed by the fuzzy AHP approach. Findings identify that steam methane reforming is the best feasible hydrogen production method in Korea. Key determinants include investment costs in equipment and market size, while spillover effects, human resource development, and environmental contributions are less influential indirect benefits. Ebadi Torkayesh et al. (2024) analyzed some of the barriers to renewable fuel market development within the German transport sector. Combining an enhanced version of a decision-making technique using type-2 neutrosophic numbers, K-means clustering, and interpretive structural modeling, some of the major restrictions as identified are insufficient renewable energy policies and poor coordination in supply chain management, considering high technologies for conversion challenge. Land and maritime transport is most seriously affected, while aviation and rail are less affected. The findings highlight a need for the development of better policies and coordination to promote renewable fuel use. Osorio-Tejada et al. (2017) developed a multi-criteria methodology for the sustainability evaluation of clean-fuel technologies in freight transport, with a focus on liquefied natural gas as an already available alternative to diesel oil. Integrating environmental, economic, and social aspects, besides those on vehicle, infrastructure, and fuel, this methodology incorporated stakeholder's judgments through semi-structured interviews, with data analysis being performed through the AHP approach. A case study in Spain compared liquefied natural gas with hydrotreated vegetable oil and diesel; liquefied natural gas is shown to be an attractive alternative fuel if the decision-makers use social and environmental criteria and legislation ensures that natural gas taxes are kept low. Results emphasize that to be successful long-term, an alternative fuel must have significant stakeholder integration and/or robust methodologies.

Kügemann & Polatidis (2019) systematically reviewed the application of MCDM methods for evaluating road transportation fuels and vehicles. Analyzing 40 relevant studies, they identified 41 commonly used evaluation criteria, which can guide future research. The review highlighted a lack of scientific rigor and standardization in criteria selection, recommending the life cycle sustainability assessment methodology as a reference framework. Comparative analyses have also shown that MCDM results are generally consistent across studies with similar setups, regardless of the specific method used. Electricity and ethanol emerge as favorable options for light vehicles, while gaseous fuels are better suited for heavy vehicles, though deviations arise due to context-specific factors and weighting schemes. Brainy et al. (2024) addressed the challenges of choosing cleaner fuel alternatives for the transportation industry, which is very important for economic prosperity but faces challenges such as fossil fuel scarcity, volatile crude oil prices, urbanization, and stringent environmental regulations. A decision-support framework using aggregation operators in a linear diophantine hesitant fuzzy setting was proposed. Two operators, the linear diophantine hesitant fuzzy weighted average and the weighted geometric operators, were designed for aggregating relevant data. They applied this framework to assess clean fuel alternatives for transportation in India through insights provided by comparative and sensitivity analyses. Hansson et al. (2019) looked at the prospects of seven alternative maritime fuels in 2030, relative to environmental and climate impacts from shipping. They applied a MCDM approach by ranking liquefied natural gas, liquefied biogas, fossil and renewable methanol, hydrogen for fuel cells-from natural gas or renewable electricity, hydrotreated vegetable oil, and heavy fuel oil against ten economic, environmental, technical, and social criteria. The ranking depended very much on the stakeholder preferences. Shipowners, fuel producers, and engine manufacturers focus on economic factors such as fuel price and rank liquefied natural gas, heavy fuel oil, and fossil methanol in the top. Swedish government representatives, however, emphasized environmental and social criteria and placed renewable hydrogen, renewable methanol, and hydrotreated vegetable oil highest. Results also indicated that renewable marine fuels will require policy support.

Mehra et al. (2024) presented a systematic decision framework using multiple MCDM techniques in order to evaluate various renewable diesel production technologies as viable alternatives to conventional diesel. A total of five production methods were evaluated against fifteen sustainability criteria. Rankings computed using the MOORA, VIKOR, and COPRAS techniques integrated criteria weights from AHP and CRITIC methods. The results identified FT diesel as the most suitable alternative followed by green diesel-I, and feedstock price and PM2.5 emissions as the most influential criteria. Mostafaeipour et al. (2021) evaluated the suitability of 17 regions for wind-powered hydrogen production using 16 sub-criteria across technical, economic, social and environmental factors. Based on an integrated hybrid of BWM, EDAS, WASPAS, ARAS and WSM techniques, the analysis identified Levelized Cost of Electricity, Levelized Cost of Hydrogen and Annual Energy Production to be the most critical factors in the analysis. Nukus, Buhara, and Kungrad emerged as the top locations, with a wind-powered hydrogen plant in Nukus capable of producing 4432.7 MW of power and 71.752 tons of hydrogen annually using 2000 kW turbines.

3. The extended IT2F-VIKOR with possibility degrees

In this section, the Bonferroni aggregation operator and other basic concepts of interval type-2 fuzzy sets that were crucial during the modeling phase are explained.

Let X be the universe of discourse. The type-2 fuzzy set (T2FS) ψ defined on X can be denoted as:

$$\psi = \{((x, u), \mu_{\psi}(x, u)) \,|\, \forall x \in X, \forall u \in J_x \subseteq [0, 1]\} \tag{1}$$

where x is the primary variable, $J_x \subseteq [0, 1]$ is the primary membership function, and u is the secondary variable.

The Eq. (1) can also be written as follows:

$$\psi = \int_{x \in X} \int_{u \in J_x} \mu_{\psi}(x, u)/(x, u) = \int_{x \in X} \left(\int_{u \in J_x} \mu_{\psi}(x, u)/u \right) /x \tag{2}$$

where $\int_{u \in J_x} \mu_{\psi}(x, u)/u$ is the second membership at x. The type-2 fuzzy set ψ is shown as Fig. 1 (Xu et al., 2019). Fig. 2 illustrates interval type-2 trapezoidal fuzzy set (Xu et al., 2019).

Let $\widetilde{\widetilde{\psi}} = [(\tau_1^U, \tau_2^U, \tau_3^U, \tau_4^U; H_1(\psi^U), H_2(\psi^U)), (\tau_1^L, \tau_2^L, \tau_3^L, \tau_4^L; H_1(\psi^L), H_2(\psi^L))]$ and $\widetilde{\widetilde{\phi}} = [(\upsilon_1^U, \upsilon_2^U, \upsilon_3^U, \upsilon_4^U; H_1(\phi^U), H_2(\phi^U)), (\upsilon_1^L, \upsilon_2^L, \upsilon_3^L, \upsilon_4^L; H_1(\phi^L), H_2(\phi^L))]$ be two IT2FSs in X that are not negative.

These are the definitions for the addition and multiplication operations in these two IT2FSs (Xu et al., 2019):

$$\widetilde{\widetilde{\psi}} + \widetilde{\widetilde{\phi}} = \begin{bmatrix} (\tau_1^U + \upsilon_1^U, \tau_2^U + \upsilon_2^U, \tau_3^U + \upsilon_3^U, \tau_4^U + \upsilon_4^U; \min\{H_1(\psi^L), H_1(\phi^L)\}, \min\{H_2(\psi^L), H_2(\phi^L)\}), \\ (\tau_1^L + \upsilon_1^L, \tau_2^L + \upsilon_2^L, \tau_3^L + \upsilon_3^L, \tau_4^L + \upsilon_4^L; \min\{H_1(\psi^U), H_1(\phi^U)\}, \min\{H_2(\psi^U), H_2(\phi^U)\}) \end{bmatrix} \tag{3}$$

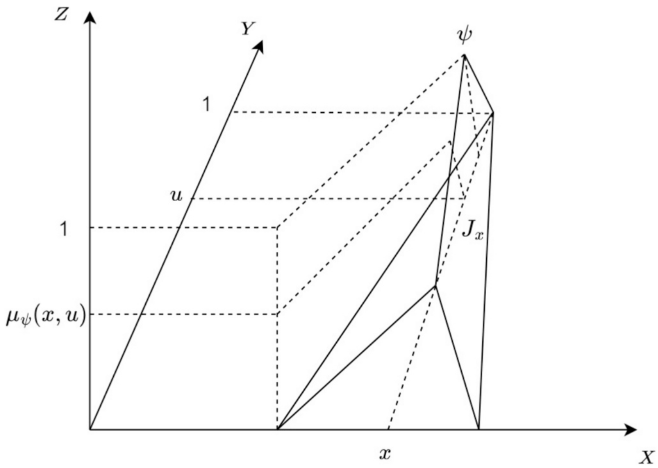

Fig. 1. Type-2 fuzzy set ψ.

$$\tilde{\tilde{\psi}} \otimes \tilde{\tilde{\phi}} = \begin{bmatrix} \left(\tau_1^U.\upsilon_1^U, \tau_2^U.\upsilon_2^U, \tau_3^U.\upsilon_3^U, \tau_4^U.\upsilon_4^U; \min\{H_1(\psi^L), H_1(\phi^L)\}, \min\{H_2(\psi^L), H_2(\phi^L)\}\right), \\ \left(\tau_1^L.\upsilon_1^L, \tau_2^L.\upsilon_2^L, \tau_3^L.\upsilon_3^L, \tau_4^L.\upsilon_4^L; \min\{H_1(\psi^U), H_1(\phi^U)\}, \min\{H_2(\psi^U), H_2(\phi^U)\}\right) \end{bmatrix} \tag{4}$$

$$k\tilde{\tilde{\psi}} = \left[\left(k\tau_1^U, k\tau_2^U, k\tau_3^U, k\tau_4^U; H_1(\psi^U), H_2(\psi^U)\right), \left(k\tau_1^L, k\tau_2^L, k\tau_3^L, k\tau_4^L; H_1(\psi^L), H_2(\psi^L)\right)\right] \tag{5}$$

$k > 0$

Now our approach, which consists of four main steps including data collection and aggregation, construction of the new possibility degree-based decision matrix, determination of ideal solutions and calculation of VIKOR indicators, is elaborated throughly.

Step 1. Aggregation of experts' judgements

In this step, the reviews and judgements of the experts is combined to

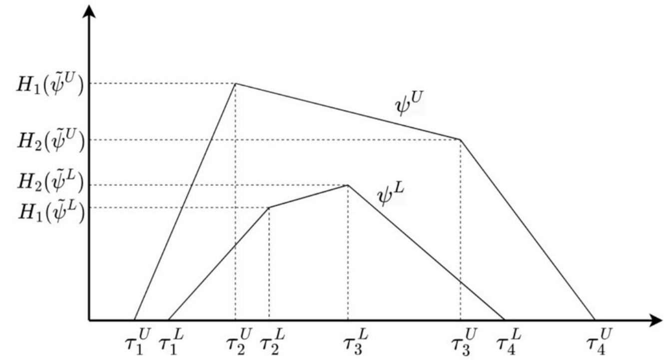

Fig. 2. Interval type-2 fuzzy set (IT2FS) ψ.

obtain a single value for further evaluations which consists of all uncertainties regarding subjective judgements of several experts.

Let $\tilde{\tilde{\psi}}_i = \left[\left(\tau_{1i}^U, \tau_{2i}^U, \tau_{3i}^U, \tau_{4i}^U; H_1(\phi_i^U), H_2(\phi_i^U)\right), \left(\tau_{1i}^L, \tau_{2i}^L, \tau_{3i}^L, \tau_{4i}^L; H_1(\phi_i^L), H_2(\phi_i^L)\right)\right]$, $(i = 1, 2, \cdots, n)$ be a set of interval type-2 trapezoidal fuzzy variables whose weight vector is $w = (w_1, w_2, \cdots, w_n)$ and $\sum_{i=1}^n w_i = 1$. The interval type-2 fuzzy Bonferroni mean (IT2FBM) is calculated as follows (Gong et al., 2016):

$$\text{IT2FBM}^{p,q}\left(\tilde{\tilde{\psi}}_1, \tilde{\tilde{\psi}}_2, \cdots, \tilde{\tilde{\psi}}_n\right) = \left[\tilde{\psi}^U, \tilde{\psi}^L\right] \tag{6}$$

where,

$\tilde{\psi}^U =$

$$\left(\begin{array}{c} \left(\frac{1}{n(n-1)}\sum_{i,j=1,i\neq j}^{l}\left(n.w_i.\tau_{1i}^U\right)^p\left(n.w_j.\tau_{1j}^U\right)^q\right)^{\frac{1}{p+q}}, \left(\frac{1}{n(n-1)}\sum_{i,j=1,i\neq j}^{l}\left(n.w_i.\tau_{2i}^U\right)^p\left(n.w_j.\tau_{2j}^U\right)^q\right)^{\frac{1}{p+q}}, \\ \left(\frac{1}{n(n-1)}\sum_{i,j=1,i\neq j}^{l}\left(n.w_i.\tau_{3i}^U\right)^p\left(n.w_j.\tau_{3j}^U\right)^q\right)^{\frac{1}{p+q}}, \left(\frac{1}{n(n-1)}\sum_{i,j=1,i\neq j}^{l}\left(n.w_i.\tau_{4i}^U\right)^p\left(n.w_j.\tau_{4j}^U\right)^q\right)^{\frac{1}{p+q}}; \\ min\{H_1(\psi_i^U)\}, min\{H_2(\psi_i^U)\} \end{array} \right) \tag{7}$$

$$\tilde{\tilde{\psi}}^L = \left(\begin{array}{c} \left(\frac{1}{n(n-1)}\sum_{i,j=1,i\neq j}^{l}\left(n.w_i.\tau^L_{1i}\right)^p\left(n.w_j.\tau^L_{1j}\right)^q\right)^{\frac{1}{p+q}}, \left(\frac{1}{n(n-1)}\sum_{i,j=1,i\neq j}^{l}\left(n.w_i.\tau^L_{2i}\right)^p\left(n.w_j.\tau^L_{2j}\right)^q\right)^{\frac{1}{p+q}}, \\ \left(\frac{1}{n(n-1)}\sum_{i,j=1,i\neq j}^{l}\left(n.w_i.\tau^L_{3i}\right)^p\left(n.w_j.\tau^L_{3j}\right)^q\right)^{\frac{1}{p+q}}, \left(\frac{1}{n(n-1)}\sum_{i,j=1,i\neq j}^{l}\left(n.w_i.\tau^L_{4i}\right)^p\left(n.w_j.\tau^L_{4j}\right)^q\right)^{\frac{1}{p+q}}; \\ min\{H_1(\psi^L_i)\}, min\{H_2(\psi^L_i)\} \end{array} \right) \tag{8}$$

Step 2. Construction of the new possibility-based decision matrix

In this step, the aggregated values from Step 1 are taken into account to obtain the possibilities and construct the novel possibility-based decision matrix.

For two IT2FSs $\tilde{\tilde{\psi}} = [(\tau^U_1, \tau^U_2, \tau^U_3, \tau^U_4; H(\psi^U)), (\tau^L_1, \tau^L_2, \tau^L_3, \tau^L_4; H(\psi^L))]$ and $\tilde{\tilde{\phi}} = [(\upsilon^U_1, \upsilon^U_2, \upsilon^U_3, \upsilon^U_4; H(\phi^U)), (\upsilon^L_1, \upsilon^L_2, \upsilon^L_3, \upsilon^L_4; H(\phi^L))]$, the value $L\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right)$ defines the possibility that $\tilde{\tilde{\phi}}$ is not larger than $\tilde{\tilde{\psi}}$ and will be obtained by the mean of lower and upper possibilities $L^-\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right)$ and $L^+\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right)$ respectively. These lower, upper, and mean possibilities were obtained as follows [3]:

The lower possibility

$$L^-\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right) = max\left\{1 - \max\left[\frac{\sum_{\xi=1}^{4}\max\left(\upsilon^U_{\xi-} - \tau^L_\xi, 0\right) + \left(\upsilon^U_4 - \tau^L_1\right) + 2\max\left(h^U_\phi - h^L_\psi, 0\right)}{\sum_{\xi=1}^{4}\left|\upsilon^U_\xi - \tau^L_\xi\right| + \left(\tau^L_4 - \tau^L_1\right) + \left(\upsilon^U_4 - \upsilon^U_1\right) + 2\left|h^U_\phi - h^L_\psi\right|}, 0\right], 0\right\} \tag{9}$$

The upper possibility

$$L^+\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right) = \max\left\{1 - \max\left[\frac{\sum_{\xi=1}^{4}\max\left(\upsilon^L_\xi - \tau^U_\xi, 0\right) + \left(\upsilon^L_4 - \tau^U_1\right) + 2\max\left(h^L_\phi - h^U_\psi, 0\right)}{\sum_{\xi=1}^{4}\left|\upsilon^L_\xi - \tau^U_\xi\right| + \left(\tau^U_4 - \tau^U_1\right) + \left(\upsilon^L_4 - \upsilon^L_1\right) + 2\left|h^L_\phi - h^U_\psi\right|}, 0\right], 0\right\} \tag{10}$$

The overall possibility

$$L\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right) = \frac{1}{2}\left(L^-\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right) + L^+\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right)\right) \tag{11}$$

The lower $L^-\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right)$ and upper $L^+\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right)$ possibilities of the preference relation $\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}$ fulfills the following properties: (1) $0 \leq L^-\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right) \leq 1$; (2) $0 \leq L^+\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right) \leq 1$; (3) $L^-\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right) + L^+\left(\tilde{\tilde{\psi}} \geq \tilde{\tilde{\phi}}\right) = 1$.

The alternative A_i performs better on a benefit criterion $c_j \in C_I$ if $\tilde{\tilde{\psi}}_{ij}$ has a high possibility of being greater than or equal to $\tilde{\tilde{\psi}}_{i'j}$ for other $n-1$ alternatives, for $i' = 1, 2, ..., n-1$ and $i \neq i'$. In contrast, alternative A_i performs better in a cost criterion $c_j \in C_{II}$, if $\tilde{\tilde{\psi}}_{ij}$ has a high possibility of being less than or equal to $\tilde{\tilde{\psi}}_{i'j}$ for other $n-1$ alternatives. The possibility-based performance index of $\tilde{\tilde{\psi}}_{ij}$ for benefit and cost criteria will be obtained by [3]:

$$P_{\tilde{\tilde{\psi}}_{i,j}} = \begin{cases} \sum_{i'=1,i'\neq i}^{n} L\left(\tilde{\tilde{\psi}}_{ij} \geq \tilde{\tilde{\psi}}_{i'j}\right) \text{if} c_j \in C_I \\ n - 1 - \sum_{i'=1,i'\neq i}^{n} L\left(\tilde{\tilde{\psi}}_{ij} \geq \tilde{\tilde{\psi}}_{i'j}\right) \text{if} c_j \in C_{II} \end{cases} \tag{12}$$

The decision matrix with *n* rows and *m* columns contains information for alternative ratings regarding the criteria. The rows represent the number of alternative s and the columns indicate the number of criteria. Assume that $P_{\tilde{\tilde{\psi}}_{i,j}}$ is the obtained possibility-based performance index for alternative i in response to criterion *j*. The new decision matrix is formed as follows:

$$Y_{n,m} = \begin{bmatrix} P_{\tilde{\tilde{\psi}}_{1,1}} & P_{\tilde{\tilde{\psi}}_{1,2}} & \cdots & P_{\tilde{\tilde{\psi}}_{1,m}} \\ P_{\tilde{\tilde{\psi}}_{2,1}} & P_{\tilde{\tilde{\psi}}_{2,2}} & \cdots & P_{\tilde{\tilde{\psi}}_{2,m}} \\ \vdots & \vdots & \vdots & \vdots \\ P_{\tilde{\tilde{\psi}}_{n,1}} & P_{\tilde{\tilde{\psi}}_{n,2}} & \cdots & P_{\tilde{\tilde{\psi}}_{n,m}} \end{bmatrix} \tag{13}$$

Step 3. Determination of positive and negative values

In Step 3, the positive and negative ideal solutions are calculated

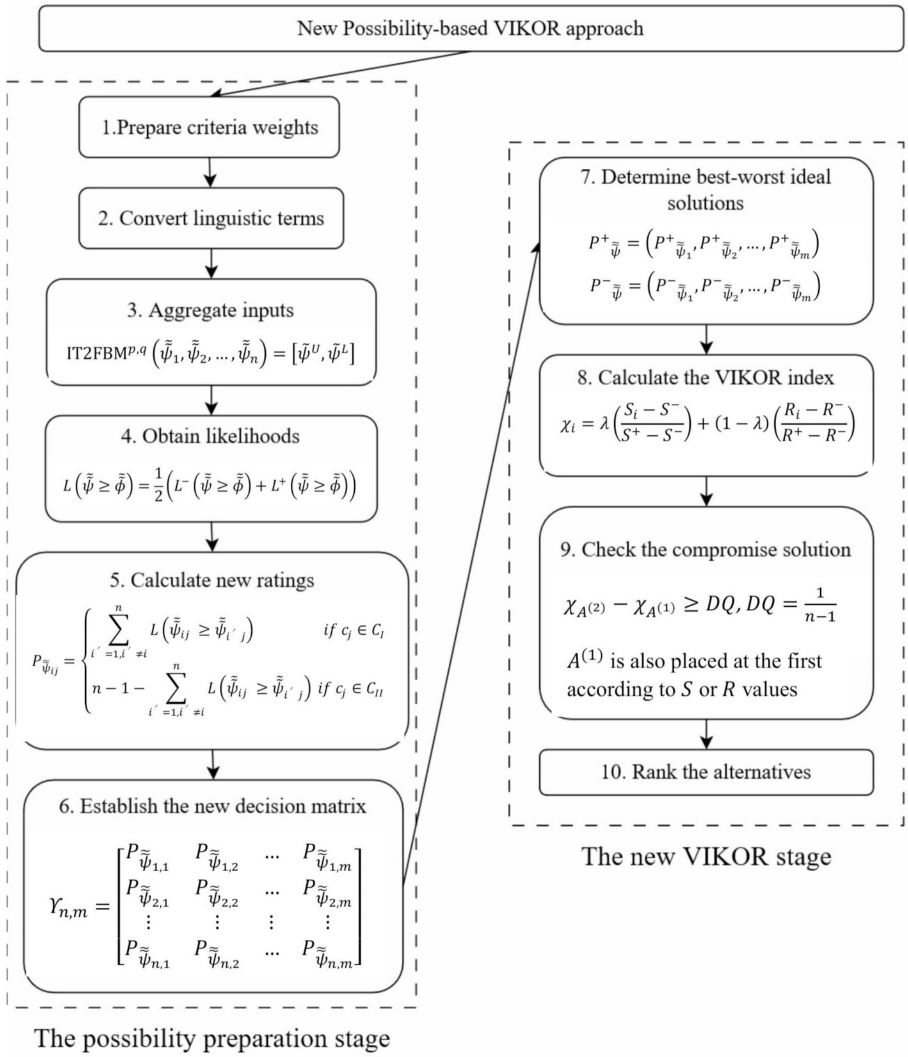

Fig. 3. The structure of new VIKOR steps.

based on the decision matrix in Step 2.

For determining the positive vector $P^{+}_{\tilde{\tilde{\psi}}}$, the highest value among every column will be chosen, representing the best performing value among alternatives in response to criterion j as follows:

$$P^{+}_{\tilde{\tilde{\psi}}} = \left(P^{+}_{\tilde{\tilde{\psi}}_1}, P^{+}_{\tilde{\tilde{\psi}}_2}, \cdots, P^{+}_{\tilde{\tilde{\psi}}_m}\right) = \left(\max\left[P_{\tilde{\tilde{\psi}}_{1,1}}, P_{\tilde{\tilde{\psi}}_{2,1}}, \cdots, P_{\tilde{\tilde{\psi}}_{n,1}}\right], \max\left[P_{\tilde{\tilde{\psi}}_{1,2}}, P_{\tilde{\tilde{\psi}}_{2,2}}, \cdots, P_{\tilde{\tilde{\psi}}_{n,2}}\right], \cdots, \max\left[P_{\tilde{\tilde{\psi}}_{1,m}}, P_{\tilde{\tilde{\psi}}_{2,m}}, \cdots, P_{\tilde{\tilde{\psi}}_{n,m}}\right]\right) \tag{14}$$

Similarly, for determining the negative vector $P^{-}_{\tilde{\tilde{\psi}}}$, the lowest value of decision matrix's columns represents the worst performing value among alternatives in response to criterion j as follows:

$$P^{-}_{\tilde{\tilde{\psi}}} = \left(P^{-}_{\tilde{\tilde{\psi}}_1}, P^{-}_{\tilde{\tilde{\psi}}_2}, \cdots, P^{-}_{\tilde{\tilde{\psi}}_m}\right) = \left(\min\left[P_{\tilde{\tilde{\psi}}_{1,1}}, P_{\tilde{\tilde{\psi}}_{2,1}}, \cdots, P_{\tilde{\tilde{\psi}}_{n,1}}\right], \min\left[P_{\tilde{\tilde{\psi}}_{1,2}}, P_{\tilde{\tilde{\psi}}_{2,2}}, \cdots, P_{\tilde{\tilde{\psi}}_{n,2}}\right], \cdots, \min\left[P_{\tilde{\tilde{\psi}}_{1,m}}, P_{\tilde{\tilde{\psi}}_{2,m}}, \cdots, P_{\tilde{\tilde{\psi}}_{n,m}}\right]\right) \tag{15}$$

Step 4. Calculation of the VIKOR indicators and alternative ranking

In Step 4, the indicators of the VIKOR approach are calculated to help us rank the alternatives.

After calculating the ideal solutions, the next objective is to calculate the group utility measure S_i and the regret measure R_i for each of the possible alternatives with the assistance of the normalized Euclidean distance and the normalized weights of criteria as follows:

Table 1
The possibility values for the pairwise comparison of alternatives.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
$L\left(\widetilde{\psi}_{1j} \geq \widetilde{\psi}_{2j}\right)$	0.958	0.791	0.990	0.057	0.349	0.037	0.703	0.649
$L\left(\widetilde{\psi}_{1j} \geq \widetilde{\psi}_{3j}\right)$	0.789	0.872	0.805	0.014	0.370	0.779	0.162	0.220
$L\left(\widetilde{\psi}_{1j} \geq \widetilde{\psi}_{4j}\right)$	0.976	0.023	0.978	0.021	0.296	0.801	0.294	0.734
$L\left(\widetilde{\psi}_{1j} \geq \widetilde{\psi}_{5j}\right)$	0.853	0.872	0.748	0.758	0.0	0.800	0.264	0.535
$L\left(\widetilde{\psi}_{2j} \geq \widetilde{\psi}_{1j}\right)$	0.042	0.209	0.010	0.943	0.651	0.963	0.297	0.351
$L\left(\widetilde{\psi}_{2j} \geq \widetilde{\psi}_{3j}\right)$	0.130	0.621	0.044	0.215	0.501	0.990	0.065	0.136
$L\left(\widetilde{\psi}_{2j} \geq \widetilde{\psi}_{4j}\right)$	0.656	0.003	0.318	0.249	0.390	0.994	0.131	0.602
$L\left(\widetilde{\psi}_{2j} \geq \widetilde{\psi}_{5j}\right)$	0.194	0.621	0.032	0.979	0.0	0.996	0.119	0.384
$L\left(\widetilde{\psi}_{3j} \geq \widetilde{\psi}_{1j}\right)$	0.211	0.128	0.195	0.986	0.630	0.221	0.838	0.780
$L\left(\widetilde{\psi}_{3j} \geq \widetilde{\psi}_{2j}\right)$	0.870	0.379	0.956	0.785	0.499	0.010	0.935	0.864
$L\left(\widetilde{\psi}_{3j} \geq \widetilde{\psi}_{4j}\right)$	0.920	0.0	0.922	0.553	0.404	0.535	0.732	0.904
$L\left(\widetilde{\psi}_{3j} \geq \widetilde{\psi}_{5j}\right)$	0.639	0.500	0.395	1.0	0.003	0.522	0.681	0.801
$L\left(\widetilde{\psi}_{4j} \geq \widetilde{\psi}_{1j}\right)$	0.024	0.977	0.022	0.979	0.704	0.199	0.706	0.266
$L\left(\widetilde{\psi}_{4j} \geq \psi_{2j}\right)$	0.344	0.997	0.682	0.751	0.610	0.006	0.869	0.398
$L\left(\widetilde{\psi}_{4j} \geq \widetilde{\psi}_{3j}\right)$	0.080	1.0	0.078	0.447	0.596	0.465	0.268	0.096
$L\left(\widetilde{\psi}_{4j} \geq \widetilde{\psi}_{5j}\right)$	0.127	1.0	0.051	1.0	0.012	0.485	0.444	0.291
$L\left(\widetilde{\psi}_{5j} \geq \widetilde{\psi}_{1j}\right)$	0.147	0.128	0.252	0.242	1.0	0.200	0.736	0.465
$L\left(\widetilde{\psi}_{5j} \geq \widetilde{\psi}_{2j}\right)$	0.806	0.379	0.968	0.021	1.0	0.004	0.881	0.616
$L\left(\widetilde{\psi}_{5j} \geq \widetilde{\psi}_{3j}\right)$	0.361	0.500	0.605	0.0	0.997	0.478	0.319	0.199
$L\left(\widetilde{\psi}_{5j} \geq \widetilde{\psi}_{4j}\right)$	0.873	0.0	0.949	0.0	0.988	0.515	0.556	0.709

Table 2
The new possibility-based decision matrix and VIKOR indicators.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	S_i	R_i
$P_{\tilde{\tilde{\psi}}_{1j}}$	3.576	2.558	3.521	0.85	1.015	2.417	1.423	2.138	0.452	0.145
$P_{\tilde{\tilde{\psi}}_{2j}}$	1.022	1.454	0.404	2.386	1.542	3.943	0.612	1.473	0.719	0.221
$P_{\tilde{\tilde{\psi}}_{3j}}$	2.64	1.007	2.468	3.324	1.536	1.288	3.186	3.349	0.461	0.230
$P_{\tilde{\tilde{\psi}}_{4j}}$	0.575	3.974	0.833	3.177	1.922	1.155	2.287	1.051	0.533	0.260
$P_{\tilde{\tilde{\psi}}_{5j}}$	2.187	1.007	2.774	0.263	3.985	1.197	2.492	1.989	0.652	0.230
$P^{+}_{\tilde{\tilde{\psi}}}$	3.576	3.974	3.521	3.324	3.985	3.943	3.186	3.349		
$P^{-}_{\tilde{\tilde{\psi}}}$	0.575	1.007	0.404	0.263	1.015	1.155	0.612	1.051		

$$S_i = \sum_{j=1}^{t} w_j \frac{d\left(P^{+}_{\tilde{\tilde{\psi}}}, P_{\tilde{\tilde{\psi}}_{i,j}}\right)}{d(P^{+}_{\tilde{\tilde{\psi}}}, P^{-}_{\tilde{\tilde{\psi}}})} \tag{16}$$

$$R_i = \max_j w_j \frac{d\left(P^{+}_{\tilde{\tilde{\psi}}}, P_{\tilde{\tilde{\psi}}_{i,j}}\right)}{d(P^{+}_{\tilde{\tilde{\psi}}}, P^{-}_{\tilde{\tilde{\psi}}})} \tag{17}$$

where $d\left(P^{+}_{\tilde{\tilde{\psi}}}, P_{\tilde{\tilde{\psi}}_{i,j}}\right)$ is the distance between two crisp numbers $P^{+}_{\tilde{\tilde{\psi}}}$ and $P_{\tilde{\tilde{\psi}}_{i,j}}$, obtained by the absolute value of $\left|P^{+}_{\tilde{\tilde{\psi}}} - P_{\tilde{\tilde{\psi}}_{i,j}}\right|$. $d(P^{+}_{\tilde{\tilde{\psi}}}, P^{-}_{\tilde{\tilde{\psi}}})$ also defines the distance between two crisp numbers $P^{+}_{\tilde{\tilde{\psi}}}$ and $P^{-}_{\tilde{\tilde{\psi}}}$, obtained by the absolute value of $\left|P^{+}_{\tilde{\tilde{\psi}}} - P^{-}_{\tilde{\tilde{\psi}}}\right|$.

Now, the maximum and minimum values of S_i and R_i are calculated as follows:

$$S^{+} = \max_i S_i \tag{18}$$

$$S^{-} = \min_i S_i \tag{19}$$

$$R^{+} = \max_i R_i \tag{20}$$

$$R^{-} = \min_i R_i \tag{21}$$

In order to assess the ranking measure χ_i for the alternative A_i, the characteristics of the group utility S_i and individual regret R_i are combined as follows:

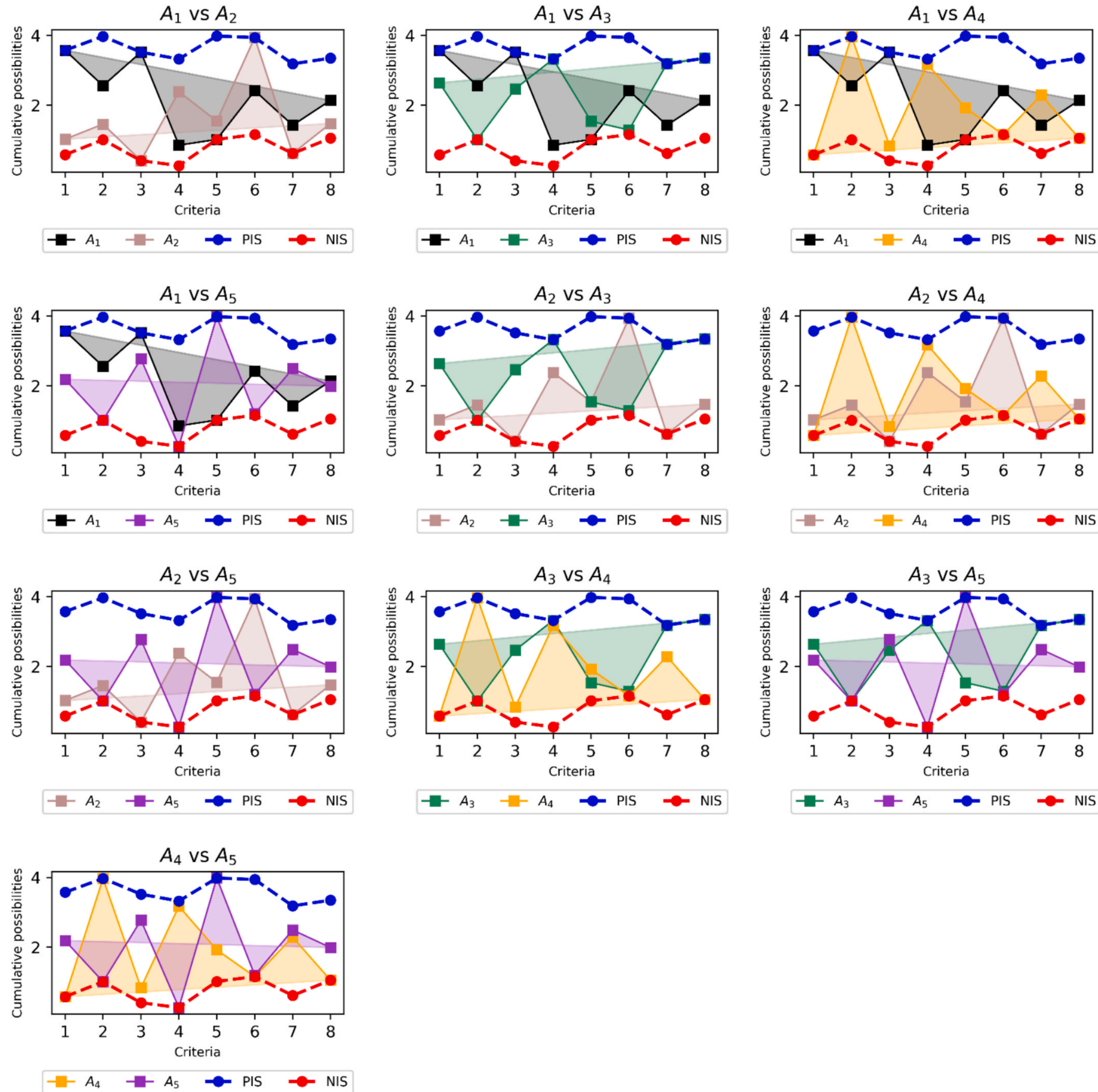

Fig. 4. Pairwise comparison of alternatives.

$$\chi_i = \lambda\left(\frac{S_i - S^-}{S^+ - S^-}\right) + (1-\lambda)\left(\frac{R_i - R^-}{R^+ - R^-}\right) \tag{22}$$

Where the parameter λ represents the weight of strategy for the majority of the criteria (the largest group utility), and is an extremely important factor in the assessment of the compromise solution. The alternatives that are placed first and second respectively, in terms of χ are designated by $A^{(1)}$ and $A^{(2)}$. If the following conditions are met, the compromise solution includes the alternative $A^{(1)}$:

$\chi_{A^{(2)}} - \chi_{A^{(1)}} \geq DQ$, where $DQ = \frac{1}{n-1}$ and n defines the total number of alternatives.
The alternative $A^{(1)}$ is also placed at the first position in the ranking order according to S or R values.

Fig. 3 presents the steps of applying the proposed possibility-based VIKOR approach.

4. Validation and case study

4.1. Comparative analysis

This section resolves a numerical case proposed by Liu et al. (2018), which utilized a similar IT2F-VIKOR but without possibilities, to demonstrate the validity of the conclusions drawn from the proposed approach. The numerical case must evaluate each of the five suppliers (A_1, A_2, A_3, A_4, and A_5) and choose one to work with on a long-term basis. Eight criteria including “price of product”, “Profit on product”, “Transportation cost”, “Waste management”, “Green manufacturing”,

Table 3
The group utility measure S_i and the regret measure R_i for five alternatives.

S_i	R_i	S^+	S^-	R^+	R^-	χ_i
0.452	0.145	0.719	0.452	0.260	0.145	0
0.719	0.221					0.830
0.461	0.230					0.386
0.533	0.260					0.651
0.652	0.230					0.744

Table 4
Comparative analysis of different approaches.

Reference	Approach	Ranking variables	Final ranking
K. Liu et al. (2018)	IT2F-VIKOR	$Q_1 = 0.54$, $Q_2 = 1$, $Q_3 = 0.81$, $Q_4 = 0.85$, $Q_5 = 0.82$	$A_1 > A_3 > A_5 > A_4 > A_2$
T. Wu & Liu (2016)	IT2F-ANP	$R_1 = 4.81$, $R_2 = 3.94$, $R_3 = 4.57$, $R_4 = 4.04$, $R_5 = 4.13$	$A_1 > A_3 > A_5 > A_4 > A_2$
S. M. Chen & Hong (2014)	IT2F-TOPSIS	$C(A_1) = 0.66$, $C(A_2) = 0.40$, $C(A_3) = 0.49$, $C(A_4) = 0.43$, $C(A_5) = 0.45$	$A_1 > A_3 > A_5 > A_4 > A_2$
T. Y. Chen (2015)	Likelihoods of IT2F preference relations	$\varepsilon_1 = 4.67$, $\varepsilon_2 = 3.10$, $\varepsilon_3 = 4.56$, $\varepsilon_4 = 4.22$, $\varepsilon_5 = 3.46$	$A_1 > A_3 > A_4 > A_5 > A_2$
This study	Possibility-based IT2F-VIKOR	$\chi_1 = 0$, $\chi_2 = 0.830$, $\chi_3 = 0.386$, $\chi_4 = 0.651$, $\chi_5 = 0.744$	$A_1 > A_3 > A_4 > A_5 > A_2$

"Green packing and labeling", "Occupational health and safety systems", and "Information disclosure" were chosen to evaluate the performance of alternatives. The weight vector for these eight criteria was selected as W = (0.26, 0.23, 0.06, 0.18, 0.1, 0.05, 0.04, 0.08). With regard to several viewpoints, including the final ranking of alternatives, we compare the suggested approach with the existing approaches. The aggregated interval type-2 fuzzy decision matrix is adopted from Liu et al. (2018) and is shown as Table A.1 in the Appendix, and the steps of the proposed approach are implemented to obtain the final ranking of alternatives. Then, the results are compared to the ones obtained by using IT2F-VIKOR (K. Liu et al., 2018), IT2F-ANP (T. Wu & Liu, 2016), and IT2F-TOPSIS (S. M. Chen & Hong, 2014).

Table 1 presents the possibility values that are obtained for the pairwise comparison of alternatives with respect to each criterion. These values are obtained to build the new possibility-based decision matrix, which is shown together with the new extended VIKOR steps in Table 2. Variables $P^{+}_{\tilde{\tilde{\psi}}}$ and $P^{-}_{\tilde{\tilde{\psi}}}$ represent the new positive and negative ideal solutions for the VIKOR approach respectively.

Fig. 4 demonstrates a pairwise comparison of the alternatives according to the components of the new decision matrix, which shows the superiority of each alternative over the other alternatives for meeting a specific criterion. The blue and red lines represent the positive and negative ideal solutions respectively. Each alternative has been assigned a unique color to be compared with the other alternatives. This kind of pairwise comparison plot is informative, since it brings information about strong and weak points of alternatives performances compared to the other alternatives.

Table 3 also indicates the group utility measure S_i and the regret measure R_i as well as final indicators which are required for ranking the alternatives using the new VIKOR approach. According to the χ_i values which are obtained for alternatives, the final ranking proposed by the new VIKOR approach is obtained as $A_1 > A_3 > A_4 > A_5 > A_2$, indicating A_1 and A_2 as the best and worst alternative respectively.

The new VIKOR constrained is also examined to make sure that the final ranking is valid:

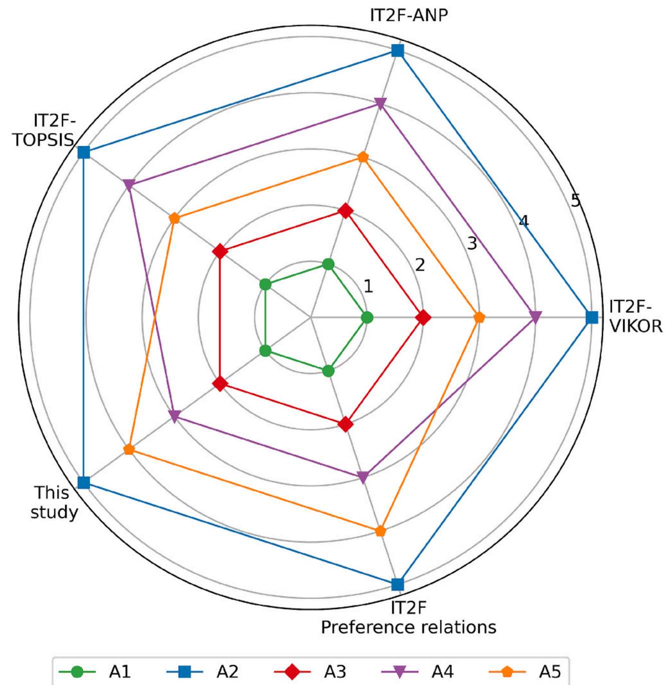

Fig. 5. Graphical comparative analysis of different approaches.

$$0.386 - 0 \geq \frac{1}{5-1} = 0.25 \tag{23}$$

Table 4 displays the final rankings that are obtained by different approaches. As shown, the proposed new VIKOR approach concludes a different ranking for alternatives, while the best and worst alternatives remained the same. Alternatives A_4 and A_5 are replaced in terms of ranking, indicating a higher amount of uncertainty coverage that the proposed approach offers. By having a look at the pairwise comparison of these two alternatives in Fig. 4, it can be inferred that both alternatives perform almost equally in terms of closeness to positive and negative ideal solutions. However, A_4 performs better in responding to criteria which have a higher importance weight. Thus, χ_4 is calculated lower than χ_5, and consequently A_4 is ranked third.

Fig. 5 also exhibits a graphical interpretation of the different approaches and the final ranking obtained by the five alternatives. The comparative analysis shows a great degree of consistency among the different methods on the best alternatives, A_1 especially ranking as the best alternative in all approaches. This uniformity suggests that A_1 is a robust option irrespective of the methodology applied and gives further weight to its suitability for being the most desirable alternative. Similarly, A_3 comes out to be the reliable second best in most of the cases, showing its stability across different evaluation techniques. Such consistency across methods underlines the reliability of these rankings while applying to decision-making situations involving fuzzy logic.

Despite this general ranking, some minor deviations in the ranks of A_4 and A_5 point out the methodological differences that naturally exist among the approaches. For example, the Likelihoods of IT2F Preference Relations method ranks A_4 over A_5, while other methods, like IT2F-TOPSIS and IT2F-ANP, rank them vice versa. These minor variations owe their existence to the different mathematical roots and computational procedures followed by each method. Such differences outline the importance of the choice of approach according to context and the requirements from a decision-making perspective.

Of particular novelty is the possibility-based IT2F-VIKOR approach of this study. Introducing possibility-based χ_i values as the criteria for ranking, this method offers a new look toward compromise solutions. The final ranking obtained from this method is also quite close to the results from other methods and thus justifies its reliability. However, its unique treatment of A_4 and A_5 indicates that this method captures nuances or priorities that might not be captured by other methods. This reflects the flexibility and possible benefits of possibility-based IT2F-VIKOR for complex decision-making problems.

4.2. Numerical case

For the case study presented in this study, experts evaluated alternative fuels (hydrogen, advanced biofuels, and electricity) against sustainability criteria-such as potential GHG reduction, economic benefits-and identified relevant market barriers, such as insufficient public acceptance and infrastructure. However, T1FSs would require experts to provide exact membership values for each criterion, which cannot capture their hesitation or uncertainty in providing ratings against vague concepts such as “high” safety or “low” environmental impact. IT2FSs let such evaluations take the form of ranges reflecting natural variability in expert opinions. For example, the expression “high” could correspond to a range of values, such as between 0.7 and 0.9, instead of being represented through a crisp value, due to linguistic ambiguity. This possibility turned out to be crucial in distinguishing highly ranked alternatives, especially when small variations in expert judgments made a remarkable impact on the ranking.

For instance, in a supply chain context, DMs have to assess various risks for suppliers, which are usually based on qualitative criteria like “delivery reliability” or “financial stability.” All of these qualitative criteria depend on subjective interpretation, and DMs may face some difficulties with accurate ratings. Using IT2FSs, an evaluation result such as “moderate reliability” can be expressed by an interval, like 0.4–0.6, reflecting the range of possible assessments due to the confidence of the decision-maker. This approach will grant more robustness to the risk ranking since it reduces the impact of too rigid classification, a possible issue when T1FSs are used. Moreover, the added layer of uncertainty given by IT2FSs permits better sensitivity analyses that can help the decision-makers to identify which risks are more sensitive due to variations in expert judgment.

In this section, a numerical case regarding freight transportation is resolved to elucidate the implementation steps of the proposed VIKOR approach.

4.2.1. Case description

Global interest in alternative fuels has increased recently due to the pressing challenges of climate change, energy security, and sustainability. As conventional fossil fuels continue to cause climate change and exhaust finite resources, the search for cleaner, more efficient, and renewable energy sources has intensified. The EU’s freight transportation industry has the potential to emit fewer greenhouse gases thanks to the use of renewable fuels. Alternative fuels, including biofuels, can cut GHG emissions in the freight transportation by 25 %, according to a comprehensive literature analysis on strategies to minimize GHG emissions in transport operations of industrial enterprises (Miklautsch & Woschank, 2022). Among transportation modes, the road mode is the main contributor to GHG emissions with a share of 71 %, accounting for 740 million tons of CO_2 equivalent in 2021. According to the recent report of the European Commission called *EU Transport in Figures* (Commission, 2021), light duty trucks, heavy duty trucks and buses account for almost 39 % of this amount. Considering the high importance of trucks for supply chains and their potential growth due to the economic prosperity of industries, GHG emissions seem to increase noticeably over the years. Thus, renewable fuel alternatives can play a significant role in decarbonization of the sector aligned with the EU 2030 and 2050 targets (Tsiropoulos et al., 2020). In this case, a case study has been resolved to address the renewable fuel selection and ranking for the freight road sector.

The suggested MCDM method can be applied to the EU’s system of freight transportation to objectively rank renewable fuel substitutes

Table 5
The sustainability criteria and market development barriers for evaluation.

Code	Criteria	Description	Positive/ Negative	Reference
Sustainability criteria				
SC_1	Promising Economic Benefits	The use of renewable fuels promotes sustainable economic growth by ensuring energy security, lowering costs, and advancing technology.	Positive	(Farghali et al., 2023; H. Wang et al., 2022)
SC_2	Low Environmental & Ecological Footprints	In order to create a cleaner and more balanced future, renewable fuels encourage sustainable resource management, limit environmental effects, and preserve biodiversity.	Positive	(Luoye Chen et al., 2021; Farghali et al., 2023)
SC_3	Potential GHG Emission Reduction	Renewable fuels provide a viable route to a cleaner future by reducing greenhouse gas emissions, and thus mitigate climate change.	Positive	(He, 2023; Prakash et al., 2020)
SC_4	High ratio of Employment & Job Creation	Renewable fuels help to create new jobs, boost the economy, and offer a variety of job possibilities within the renewable energy sector,	Positive	(Balin & Baraçli, 2017; Saraswat & Digalwar, 2021; Şengül et al., 2015)
SC_5	High Safety	Renewable fuels place a high priority on safety with regard to health, the environment, and infrastructural hazards. They provide a safe and reliable energy solution as there are no hazardous materials involved and they use decentralized energy models.	Positive	(Hansson et al., 2019; Saraswat & Digalwar, 2021; Yavuz et al., 2015)
Market development barriers				
BC_1	Lack of Public Acceptance	Despite the fact that these sustainable energy sources have positive environmental effects, public acceptability is hampered by unfamiliarity, compatibility issues, and false beliefs about efficiency.	Negative	(Balin & Baraçli, 2017; Lihong Chen & Ren, 2018; Ren & Liang, 2017)
BC_2	Insufficient Technological & Market Infrastructures	The broad use of renewable fuels faces obstacles due to limited technological	Negative	(Owusu & Asumadu-Sarkodie, 2016; Seetharaman et al., 2019)

(continued on next page)

Table 5 (*continued*)

Code	Criteria	Description	Positive/ Negative	Reference
		development and weak market infrastructures. These obstacles must be removed in order to promote the transition to renewable fuel technologies, and this may be done by enhancing research and development, investing in infrastructure, and enacting supporting laws.		
BC_3	Limited Policies and Regulations	A barrier to the widespread use of renewable fuels is limiting comprehensive laws and regulations. To offer incentives and direction, promote investments, and foster a climate that is beneficial for renewable energy projects, clear and supporting frameworks are required. A sustainable energy future may be made possible by creating strong policies and encouraging international collaboration.	Negative	(Lu et al., 2020; Seetharaman et al., 2019)
BC_4	Lack of Feedstock (raw material) Availability	The manufacturing of renewable fuels is hampered by the scarcity of raw resources. In order to address this problem and provide a dependable supply chain for the manufacture of renewable fuels, stakeholders must work together, diversify their feedstock sources, and implement sustainable agriculture methods.	Negative	(Ahorsu et al., 2018; Saleem, 2022)
BC_5	Short Travel Range	Compared to conventional fossil fuel cars, renewable fuel technologies like electricity may have a shorter driving range. This problem is being addressed by ongoing developments in energy storage and fuel cell technologies, as well as the growth of charging and refilling networks.	Negative	(Oztaysi et al., 2017; Yavuz et al., 2015)

while taking sustainability and market obstacles unique to freight road transport into consideration. This is particularly important because many earlier studies mostly concentrated on passenger road transport, which resulted in a dearth of complete solutions specifically suited to the special problems and demands of the freight sector. The proposed application closes a gap by taking freight road transport into account and guarantees that sustainable fuel alternatives are properly assessed and prioritized to produce positive environmental effect in this crucial transportation area. An accurate assessment of renewable fuel alternatives that clarifies which fuels are truly superior is possible by taking into account both sustainability and market barrier factors using the proposed approach.

The following criteria were selected based on a thorough literature review related to renewable fuels and sustainable freight transportation. Each of these criteria reflect the most important factors affecting the feasibility and sustainability of renewable fuel options in the freight sector. For example, economic benefits are basic because they define the financial viability of alternative fuels during large-scale operations, whereas GHG emission reduction directly addresses the environmental objectives responsible for the increased demand in renewable alternatives. Factors like “Lack of Public Acceptance” and “Insufficient Technological & Market Infrastructures” have been selected due to operational and social challenges created by them, generally known as major barriers to renewable fuel adoption within the transportation industries. All the above factors were rated to be highly relevant based on recent studies and ongoing challenges of the industry, which can ensure that all aspects of sustainability and market feasibility can be met in the model.

Data used in assessing each fuel alternative by these criteria were obtained from some experts in the fields of renewable fuels research and development. The experts evaluated through the defined linguistic scale, an innovative way to translate subjective evaluation into IT2FSs to accommodate uncertainty inherent in expert judgments. A first screening phase was performed with the experts to validate that all of the selected criteria brought information worthy of consideration for the analysis. The renewable fuel options selected for the alternatives, such as hydrogen, biofuels, PtX fuels, and electricity, were chosen because these fuels are receiving significant attention and focus in recent developments and discussions in the energy and transport sectors. These collectively reinforce that there is growing interest in those specific fuels as viable alternatives for freight.

The second-generation renewable fuel alternatives that pertain to current and future practice include first-generation biofuels, advanced biofuels, PtX fuels, hydrogen, and electricity. Each of them represents a different way of reducing carbon emissions and addressing the challenge of sustainability. First-generation biofuels are at the commercial stage but have perceived disadvantages in land competition and lifecycle emissions. Advanced biofuels and PtX fuels have higher environmental benefits in light of lower impact on food resources and the higher potential of circular energy usage. Hydrogen and electricity are also included since they do bear enormous potentials to revolutionize transport energy but come with challenges in infrastructure and energy storage. It spans a wide range of renewable fuels, from mature technologies like biofuels to emerging alternatives like hydrogen, and informs about the comparative advantages and limitations of each.

The alternatives that are considered for evaluation in this case are briefly explained below:

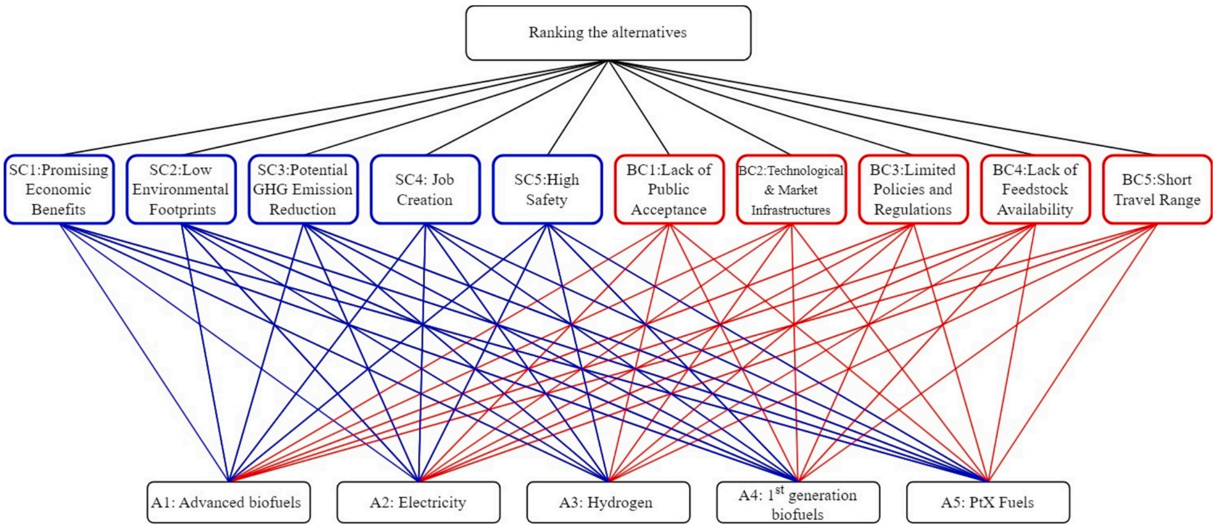

Fig. 6. The structural hierarchy of the multi-criteria assessment.

Table 6
Linguistic-to-IT2FSs scale used for evaluation of the criteria (Hendiani & Walther, 2023a).

Linguistic variables	IT2FSs for criteria
"Worst (W)"	((0, 0, 0, 1; 1, 1), (0, 0, 0, 0.5; 0.9, 0.9))
"Very Low (VL)"	((0, 1, 1, 3; 1, 1), (0.5, 1, 1, 2; 0.9, 0.9))
"Low (L)"	((1, 3, 3, 5; 1), (2, 3, 3, 4; 0.9))
"Fair (F)"	((3, 5, 5, 7; 1, 1), (4, 5, 5, 6; 0.9, 0.9))
"High (H)"	((5, 7, 7, 9; 1, 1), (6, 7, 7, 8; 0.9, 0.9))
"Very High (VH)"	((7, 9, 9, 10; 1, 1), (8, 9, 9, 9.5; 0.9, 0.9))
"Most (M)"	((9, 10, 10, 10; 1, 1), (9.5, 10, 10, 10; 0.9, 0.9))

Table 7
Linguistic-to-crisp scale used for weighting the criteria.

Linguistic variables	Corresponding weight
Very Low (VL)	1
Low (L)	2
Medium (M)	3
High (H)	4
Very High (VH)	5

Table 8
Linguistic terms for criteria weights.

Sustainability Indicators	Weight	Market Development Indicators	Weight
Promising Economic Benefits (SC_1)	H	Lack of Public Acceptance (BC_1)	VH
Low Environmental & Ecological Footprints (SC_2)	VH	Insufficient Technological & Market Infrastructures (BC_2)	L
Potential GHG Emission Reduction (SC_3)	VH	Limited Policies and Regulations (BC_3)	VH
High ratio of Employment & Job Creation (SC_4)	L	Lack of Feedstock (raw material) Availability (BC_4)	H
High Safety (SC_5)	M	Short Travel Range (BC_5)	M

First-generation biofuels, particularly ethanol and biodiesel produced from crops like maize, sugarcane, and soybeans, have certain disadvantages related to land-use competition and lifecycle greenhouse gas emissions however first-generation biofuels have helped to reduce dependence on fossil fuels and foster a culture of renewable energy.

Table 9
Linguistic terms for performance of alternatives as a pair (E_1, E_2).

	Positive criteria				
	SC_1	SC_2	SC_3	SC_4	SC_5
A_1	"L, L"	"VH, H"	"VH, VH"	"H, H"	"VH, H"
A_2	"VH, VH"	"VH, VH"	"H, VH"	"VH, VH"	"M, VH"
A_3	"VH, M"	"M, M"	"VH, VH"	"VH, VH"	"M, M"
A_4	"H, VH"	"L, L"	"VL, L"	"F, F"	"H, H"
A_5	"L, W"	"VH, H"	"VH, H"	"H, H"	"H, VH"
	Negative criteria				
	BC_1	BC_2	BC_3	BC_4	BC_5
A_1	"VH, VH"	"L, F"	"M, VH"	"VH, VH"	"VH, M"
A_2	"H, VH"	"F, H"	"F, F"	"F, F"	"F, H"
A_3	"H, H"	"F, L"	"F, L"	"F, F"	"F, F"
A_4	"F, F"	"H, H"	"H, VH"	"H, H"	"F, F"
A_5	"H, H"	"VL, L"	"VH, VH"	"M, VH"	"H, H"

Advanced biofuels, second- and third-generation biofuels, are emerging as possible substitutes for fossil fuels. These biofuels are made from non-food sources including agricultural waste, algae, or unique energy crops that don't jeopardize the availability of food. Compared to their first-generation predecessors, which were primarily produced from consumable crops like maize or sugarcane, advanced biofuels provide significant environmental benefits by restricting land-use changes and reducing carbon emissions.
Power-to-X (PtX) fuels, are the subject of an expanding corpus of study. PtX fuels are a kind of synthetic fuels that are produced by converting renewable electricity into gaseous fuels like hydrogen or methane or liquid fuels like methanol. These fuels contribute to decarbonization by allowing renewable energy to be stored for later use in a range of sectors, including transportation, manufacturing, and heating.
Hydrogen, as a fuel for electric automobiles that use fuel cells. In hydrogen fuel cells, hydrogen and oxygen are mixed to produce electricity, with the only waste being water vapor. Due to its zero emissions, hydrogen is a desirable alternative for ecologically friendly transportation. Despite the fact that infrastructure development, storage, and manufacturing of green hydrogen are still challenges, current research and development efforts aim to overcome them and fully realize the promise of hydrogen fuel cell vehicles.
Electricity is quickly becoming a significant alternative to fossil fuels with the help of resources like solar, wind, and hydro power. It reduces land-use challenges and environmental disadvantages, in

Table 10
The normalized criteria weight.

Sustainability Indicators	Weight	Normalized weight	Market Development Indicators	Weight	Normalized weight
Promising Economic Benefits (SC_1)	4	0.10526	Lack of Public Acceptance (BC_1)	5	0.13158
Low Environmental & Ecological Footprints (SC_2)	5	0.13158	Insufficient Technological & Market Infrastructures (BC_2)	2	0.05263
Potential GHG Emission Reduction (SC_3)	5	0.13158	Limited Policies and Regulations (BC_3)	5	0.13158
High ratio of Employment & Job Creation (SC_4)	2	0.05263	Lack of Feedstock (raw material) Availability (BC_4)	4	0.10526
High Safety (SC_5)	3	0.07895	Short Travel Range (BC_5)	3	0.07895

Table 11
The aggregated IT2FSs for performance of alternatives.

	Positive criteria (sustainability)				
	SC_1	SC_2	SC_3	SC_4	SC_5
A_1	((1, 3, 3, 5; 1), (2, 3, 3, 4; 0.9))	((5.92, 7.94, 7.94, 9.49; 1.0), (6.93, 7.94, 7.94, 8.72; 0.9))	((7, 9, 9, 10; 1), (8, 9, 9, 9.5; 0.9))	((5, 7, 7, 9; 1.0), (6, 7, 7, 8; 0.9))	((5.92, 7.94, 7.94, 9.49; 1.0), (6.93, 7.94, 7.94, 8.72; 0.9))
A_2	((7, 9, 9, 10; 1), (8, 9, 9, 9.5; 0.9))	((7, 9, 9, 10; 1), (8, 9, 9, 9.5; 0.9))	((5.92, 7.94, 7.94, 9.49; 1.0), (6.93, 7.94, 7.94, 8.72; 0.9))	((7, 9, 9, 10; 1), (8, 9, 9, 9.5; 0.9))	((7.94, 9.49, 9.49, 10.00; 1.0), (8.72, 9.49, 9.49, 9.75; 0.9))
A_3	((7.94, 9.49, 9.49, 10.00; 1.0), (8.72, 9.49, 9.49, 9.75; 0.9))	((9, 10, 10, 10; 1.0), (9.5, 10, 10, 10; 0.9))	((7, 9, 9, 10; 1), (8, 9, 9, 9.5; 0.9))	((7, 9, 9, 10; 1), (8, 9, 9, 9.5; 0.9))	((9, 10, 10, 10; 1.0), (9.5, 10, 10, 10; 0.9))
A_4	((5.92, 7.94, 7.94, 9.49; 1.0),(6.93, 7.94, 7.94, 8.72; 0.9))	((1, 3, 3, 5; 1), (2, 3, 3, 4; 0.9))	((0.00, 1.73, 1.73, 3.87; 1.0),(1.00, 1.73, 1.73, 2.83; 0.9))	((3, 5, 5, 7; 1.0), (4, 5, 5, 6; 0.9))	((5, 7, 7, 9; 1.0), (6, 7, 7, 8; 0.9))
A_5	((0.00, 0.00, 0.00, 2.24; 1.0), (0.00, 0.00, 0.00, 1.41; 0.9))	((5.92, 7.94, 7.94, 9.49; 1.0), (6.93, 7.94, 7.94, 8.72; 0.9))	((5.92, 7.94, 7.94, 9.49; 1.0), (6.93, 7.94, 7.94, 8.72; 0.9))	((5, 7, 7, 9; 1.0), (6, 7, 7, 8; 0.9))	((5.92, 7.94, 7.94, 9.49; 1.0), (6.93, 7.94, 7.94, 8.72; 0.9))
	Negative criteria (barriers)				
	BC_1	BC_2	BC_3	BC_4	BC_5
A_1	((7, 9, 9, 10; 1), (8, 9, 9, 9.5; 0.9))	((1.73, 3.87, 3.87, 5.92; 1.0), (2.83, 3.87, 3.87, 4.90; 0.9))	((7.94, 9.49, 9.49, 10.00; 1.0), (8.72, 9.49, 9.49, 9.75; 0.9))	((7, 9, 9, 10; 1), (8, 9, 9, 9.5; 0.9))	((7.94, 9.49, 9.49, 10.00; 1.0), (8.72, 9.49, 9.49, 9.75; 0.9))
A_2	((5.92, 7.94, 7.94, 9.49; 1.0), (6.93, 7.94, 7.94, 8.72; 0.9))	((3.87, 5.92, 5.92, 7.94; 1.0), (4.90, 5.92, 5.92, 6.93; 0.9))	((3, 5, 5, 7; 1.0), (4, 5, 5, 6; 0.9))	((3, 5, 5, 7; 1.0), (4, 5, 5, 6; 0.9))	((3.87, 5.92, 5.92, 7.94; 1.0), (4.90, 5.92, 5.92, 6.93; 0.9))
A_3	((5, 7, 7, 9; 1.0), (6, 7, 7, 8; 0.9))	((1.73, 3.87, 3.87, 5.92; 1.0), (2.83, 3.87, 3.87, 4.90; 0.9))	((1.73, 3.87, 3.87, 5.92; 1.0), (2.83, 3.87, 3.87, 4.90; 0.9))	((3, 5, 5, 7; 1.0), (4, 5, 5, 6; 0.9))	((3, 5, 5, 7; 1.0), (4, 5, 5, 6; 0.9))
A_4	((3, 5, 5, 7; 1.0), (4, 5, 5, 6; 0.9))	((5, 7, 7, 9; 1.0), (6, 7, 7, 8; 0.9))	((5.92, 7.94, 7.94, 9.49; 1.0),(6.93, 7.94, 7.94, 8.72; 0.9))	((5, 7, 7, 9; 1.0), (6, 7, 7, 8; 0.9))	((3, 5, 5, 7; 1.0), (4, 5, 5, 6; 0.9))
A_5	((5, 7, 7, 9; 1.0), (6, 7, 7, 8; 0.9))	((0.00, 1.73, 1.73, 3.87; 1.0), (1.00, 1.73, 1.73, 2.83; 0.9))	((7, 9, 9, 10; 1), (8, 9, 9, 9.5; 0.9))	((7.94, 9.49, 9.49, 10.00; 1.0), (8.72, 9.49, 9.49, 9.75; 0.9))	((5, 7, 7, 9; 1.0), (6, 7, 7, 8; 0.9))

contrast to biofuels. Electricity is positioned as a key force in the shift to a greener energy environment due to its applicability to a variety of sectors, including transportation and industry.

These fuels are being assessed not only by sustainability performance, but also by market development barriers. In other words, two types of criteria including positive (sustainability criteria) and negative (barriers to market development) are selected through literature analysis which are listed in Table 5.

Fig. 6 demonstrates a structural hierarchy of the multi-criteria assessment for the proposed illustrative case. The blue rectangles represent the sustainability criteria (positive criteria) and the red rectangles represent the market development barriers (negative criteria) that are distinguished for evaluating five fuel alternatives. For simplification during the process, each fuel has been assigned a label as follows: A_1: Advanced biofuels (2nd and 3rd generation),A_2: Electricity, A_3: Hydrogen (fuel cell for EV), A_4: 1st generation biofuels, A_5: PtX Fuels.

4.2.2. *The possibility-based VIKOR implementation steps*

In this sub-section, the steps of implementing the new VIKOR approach are elaborated in details. Before going through the steps, a few prerequisites are required to prepare data for the calculation process. These prerequisites are described below:

4.2.2.1. Prerequisite 1. Problem definition. In this step, the evaluation factors including positive and negative criteria, potential alternatives, well-suited experts for collecting data and also a linguistic-to-IT2FSs scale are determined. The linguistic scale used for this case is shown in Table 6. The linguistic variables in this table will be the options with which the experts express their judgements about the performance of each alternative in response to every single criterion. In addition, two potential experts E_1 and E_2 from R&D in field of renewable fuels are selected to judge about the performance of alternatives in response to criteria.

4.2.2.2. Prerequisite 2. Data collection. Once the problem is defined, an initial screening of the criteria is required to verify if all are relevant for the evaluation. The most relevant criteria should be filtered to prevent any impureness of the collected data. The new VIKOR approach works with a combination of criteria weights and performances to rank alternatives. Thus, a new scale for criteria weights is also required. However, for simplicity of calculations, the IT2FSs are no longer required for determining the weights of criteria. Instead, a linguistic-to-crisp scale is used to determine the weight for every single criterion in Table 7. Once the prerequisites are met, the experts are asked to submit their evaluations about each alternative. Meanwhile, the weights of the criteria are also determined by DMs.

Tables 8 and 9 show the linguistics that are collected for criteria weights and performance of the alternatives respectively.

4.2.2.3. Step 1. Data preparation. The calculation process starts with transforming the linguistic terms to numbers. For the weights of criteria, the linguistic terms will be replaced by the numbers between the range of 1 and 5 as shown in Table 7. These values are then normalized by simply dividing each weight by the sum of all weights using the following equation:

$$\overline{\omega} = \left\{\frac{\omega_1}{\sum_{i=1}^{n}\omega_i}, \frac{\omega_2}{\sum_{i=1}^{n}\omega_i}, \cdots, \frac{\omega_m}{\sum_{i=1}^{n}\omega_i}\right\} \text{and} \sum_{i=1}^{m}\overline{\omega}_i = 1 \tag{24}$$

Table 10 indicates the normalized values for criteria weights.

For the performances of alternatives, the linguistic terms will be

Table 12
The possibilities of alternatives in response to criteria.

	SC_1	SC_2	SC_3	SC_4	SC_5	BC_1	BC_2	BC_3	BC_4	BC_5
$L\left(\tilde{\psi}_{1j} \geq \tilde{\psi}_{2j}\right)$	0.0	0.190	0.810	0.086	0.085	0.810	0.076	1.0	1.0	1.0
$L\left(\tilde{\psi}_{1j} \geq \tilde{\psi}_{3j}\right)$	0.0	0.007	0.500	0.086	0.007	0.913	0.500	1.0	1.0	1.0
$L\left(\tilde{\psi}_{1j} \geq \tilde{\psi}_{4j}\right)$	0.0	1.0	1.0	0.922	0.756	1.0	0.003	0.914	0.913	1.0
$L\left(\tilde{\psi}_{1j} \geq \tilde{\psi}_{5j}\right)$	0.971	0.500	0.500	0.500	0.500	0.913	0.918	0.726	0.273	0.981
$L\left(\tilde{\psi}_{2j} \geq \tilde{\psi}_{1j}\right)$	1.0	0.810	0.190	0.914	0.915	0.190	0.924	0.0	0.0	0.0
$L\left(\tilde{\psi}_{2j} \geq \tilde{\psi}_{3j}\right)$	0.273	0.083	0.190	0.500	0.164	0.756	0.923	0.815	0.500	0.770
$L\left(\tilde{\psi}_{2j} \geq \tilde{\psi}_{4j}\right)$	0.810	1.0	1.0	1.0	0.981	0.989	0.192	0.010	0.077	0.770
$L\left(\tilde{\psi}_{2j} \geq \tilde{\psi}_{5j}\right)$	1.0	0.810	0.500	0.914	0.914	0.756	1.0	0.0	0.0	0.192
$L\left(\tilde{\psi}_{3j} \geq \tilde{\psi}_{1j}\right)$	1.0	0.993	0.500	0.914	0.993	0.087	0.500	0.0	0.0	0.0
$L\left(\tilde{\psi}_{3j} \geq \tilde{\psi}_{2j}\right)$	0.727	0.917	0.810	0.500	0.836	0.244	0.077	0.185	0.500	0.230
$L\left(\tilde{\psi}_{3j} \geq \tilde{\psi}_{4j}\right)$	0.914	1.0	1.0	1.0	1.0	0.923	0.0	0.0	0.077	0.500
$L\left(\tilde{\psi}_{3j} \geq \tilde{\psi}_{5j}\right)$	1.0	0.992	0.810	0.913	0.992	0.500	0.918	0.0	0.0	0.077
$L\left(\tilde{\psi}_{4j} \geq \tilde{\psi}_{1j}\right)$	1.0	0.0	0.0	0.078	0.244	0.0	0.997	0.086	0.087	0.0
$L\left(\tilde{\psi}_{4j} \geq \psi_{2j}\right)$	0.190	0.0	0.0	0.0	0.019	0.011	0.908	0.990	0.923	0.230
$L\left(\tilde{\psi}_{4j} \geq \tilde{\psi}_{3j}\right)$	0.086	0.0	0.0	0.0	0.0	0.077	1.0	1.0	0.923	0.500
$L\left(\tilde{\psi}_{4j} \geq \tilde{\psi}_{5j}\right)$	1.0	0.0	0.0	0.077	0.243	0.077	1.0	0.190	0.018	0.077
$L\left(\tilde{\psi}_{5j} \geq \tilde{\psi}_{1j}\right)$	0.029	0.500	0.500	0.500	0.500	0.087	0.082	0.274	0.727	0.019
$L\left(\tilde{\psi}_{5j} \geq \tilde{\psi}_{2j}\right)$	0.0	0.190	0.500	0.086	0.086	0.244	0.0	1.0	1.0	0.808
$L\left(\tilde{\psi}_{5j} \geq \tilde{\psi}_{3j}\right)$	0.0	0.008	0.190	0.087	0.008	0.500	0.082	1.0	1.0	0.923
$L\left(\tilde{\psi}_{5j} \geq \tilde{\psi}_{4j}\right)$	0.0	1.0	1.0	0.923	0.757	0.923	0.0	0.810	0.982	0.923

Table 13
The new decision matrix for five alternatives.

	SC_1	SC_2	SC_3	SC_4	SC_5	BC_1	BC_2	BC_3	BC_4	BC_5
$P_{\tilde{\tilde{\psi}}_{1j}}$	0.971	1.697	2.81	1.594	1.348	0.364	2.503	0.36	0.814	0.019
$P_{\tilde{\tilde{\psi}}_{2j}}$	3.083	2.703	1.88	3.328	2.974	1.309	0.961	3.175	3.423	2.268
$P_{\tilde{\tilde{\psi}}_{3j}}$	3.641	3.902	3.12	3.327	3.821	2.246	2.505	3.815	3.423	3.193
$P_{\tilde{\tilde{\psi}}_{4j}}$	2.276	0	0	0.155	0.506	3.835	0.095	1.734	2.049	3.193
$P_{\tilde{\tilde{\psi}}_{5j}}$	0.029	1.698	2.19	1.596	1.351	2.246	3.836	0.916	0.291	1.327

Table 14
Determination of the positive and negative ideal solutions.

	SC_1	SC_2	SC_3	SC_4	SC_5	BC_1	BC_2	BC_3	BC_4	BC_5	S_i	R_i
$P_{\tilde{\tilde{\psi}}_{1j}}$	0.971	1.697	2.81	1.594	1.348	0.364	2.503	0.36	0.814	0.019	0.701	0.132
$P_{\tilde{\tilde{\psi}}_{2j}}$	3.083	2.703	1.88	3.328	2.974	1.309	0.961	3.175	3.423	2.268	0.313	0.096
$P_{\tilde{\tilde{\psi}}_{3j}}$	3.641	3.902	3.12	3.327	3.821	2.246	2.505	3.815	3.423	3.193	0.079	0.060
$P_{\tilde{\tilde{\psi}}_{4j}}$	2.276	0	0	0.155	0.506	3.835	0.095	1.734	2.049	3.193	0.613	0.132
$P_{\tilde{\tilde{\psi}}_{5j}}$	0.029	1.698	2.19	1.596	1.351	2.246	3.836	0.916	0.291	1.327	0.629	0.110
$P^{+}_{\tilde{\tilde{\psi}}}$	3.641	3.902	3.12	3.328	3.821	3.835	3.836	3.815	3.423	3.193		
$P^{-}_{\tilde{\tilde{\psi}}}$	0.029	0	0	0.155	0.506	0.364	0.095	0.36	0.291	0.019		

replaced by the IT2FSs. Once the transformation stage is done, the Bonferroni aggregation operator shown in Eq. (6) is employed to aggregate all the judgements from two experts into one interval type-2 fuzzy set per criterion while considering all uncertainties involved with linguistic decision making. The final aggregated values for each alternative in response to criteria are shown in Table 11.

4.2.2.4. Step 2. Possibilities and likelihoods. After preparing the data, the

Table 15
The calculated VIKOR indicators for five alternatives.

Alt.	S_i	R_i	S^+	S^-	R^+	R^-	χ_i
A_1	0.701	0.132	0.701	0.079	0.132	0.060	1.000
A_2	0.313	0.096					0.437
A_3	0.079	0.060					0.000
A_4	0.613	0.132					0.929
A_5	0.629	0.110					0.793

Table 16
Comparative analysis of the results for case study.

Reference	Approach	Ranking variables	Final ranking
T. Y. Chen (2015)	Likelihoods of IT2F preference relations	$\varepsilon_1 = 2.4$, $\varepsilon_2 = 5.034$, $\varepsilon_3 = 6.652$, $\varepsilon_4 = 2.986$, $\varepsilon_5 = 2.918$	$A_3 > A_2 > A_4 > A_5 > A_1$
Hendiani and Walther (2023b)	TOPSISort-L	$C(A_1) = 0.351$, $C(A_2) = 0.641$, $C(A_3) = 0.828$, $C(A_4) = 0.432$, $C(A_5) = 0.395$	$A_3 > A_2 > A_4 > A_5 > A_1$
This study	Possibility-based IT2F-VIKOR	$\chi_1 = 1$, $\chi_2 = 0.437$, $\chi_3 = 0$, $\chi_4 = 0.929$, $\chi_5 = 0.793$	$A_3 > A_2 > A_5 > A_4 > A_1$

possibilities of IT2FSs that were aggregated in the previous step are calculated in this step by using Eq (9) to (11). Table 12 displays all the values for possibilities obtained for each pair of alternatives in response to every single criterion.

The new performances are obtained by the summation of possibilities for every alternative which represents the superiority of each alternative comparing to other alternatives. For instance, $P_{\tilde{\tilde{\psi}}_{11}}$(the new performance for alternative 1 in response to criterion 1) is obtained by summing $L\left(\tilde{\tilde{\psi}}_{11} \geq \tilde{\tilde{\psi}}_{21}\right)$, $L\left(\tilde{\tilde{\psi}}_{11} \geq \tilde{\tilde{\psi}}_{31}\right)$, $L\left(\tilde{\tilde{\psi}}_{11} \geq \tilde{\tilde{\psi}}_{41}\right)$, and $L\left(\tilde{\tilde{\psi}}_{11} \geq \tilde{\tilde{\psi}}_{51}\right)$.

The new decision matrix consisting of all the new performance values is established as Table 13. This new decision matrix will be the input for the new extended VIKOR approach in the next step.

4.2.2.5. Step 3. Possibility-based VIKOR. The input data for the new VIKOR approach is obtained in Step 2. Step 3 starts with determining the positive and negative ideal solutions from the new decision matrix. As mentioned earlier, the components for positive and negative ideal solution vectors will be determined by the maximum and minimum values of $P_{\tilde{\tilde{\psi}}_{ij}}$ respectively. For instance, the first component for the positive ideal solution vector is calculated by: $\max\left\{P_{\tilde{\tilde{\psi}}_{11}}, P_{\tilde{\tilde{\psi}}_{21}}, P_{\tilde{\tilde{\psi}}_{31}}, P_{\tilde{\tilde{\psi}}_{41}}, P_{\tilde{\tilde{\psi}}_{51}}\right\}$, which is equal to 3.641.

$P^+_{\tilde{\tilde{\psi}}}$ and $P^-_{\tilde{\tilde{\psi}}}$ in Table 14 represent the positive and negative ideal solution vectors respectively. The group utility measure S_i and the regret measure R_i are also obtained for alternatives as shown in Table 14.

The required indicators for the new VIKOR approach are computed by using Eq. (18) to (21) in Table 15.

According to χ_i values that are obtained for five alternatives, the following ranking is obtained as $A_3 > A_2 > A_5 > A_4 > A_1$, indicating A_3 or "Hydrogen" as the best and Advanced biofuels (2nd and 3rd generation) as the worst alternatives.

The new VIKOR constrained is also examined to make sure that the obtained ranking is valid:

$$0.437 - 0 \geq \frac{1}{5-1} = 0.25 \tag{25}$$

4.2.3. Comparison with other methods

In this sub-section we have compared the results of the proposed methodology with two existing methods which are most comparable in terms of using likelihoods and possibilities for fuzzy sets. Table 16 displays the final rankings that are obtained by different approaches together with the ranking variables which are used for each approach. As shown, the proposed new VIKOR approach concludes a different ranking for alternatives, while the first and last ranked alternatives remained the same. Alternatives A_4 and A_5 switch places in the ranking, suggesting that the proposed approach provides greater uncertainty coverage. A look at the pairwise comparison of these two alternatives in Fig. 8 suggests that both perform nearly equally in terms of closeness to the positive and negative ideal solutions.

In the proposed case study, A_4 and A_5 exhibit close performance across different criteria, sometimes favoring A_4 and other times favoring A_5. The observed ranking differences arise from the unique combination of possibility degrees of IT2FSs and the VIKOR method, which enhances

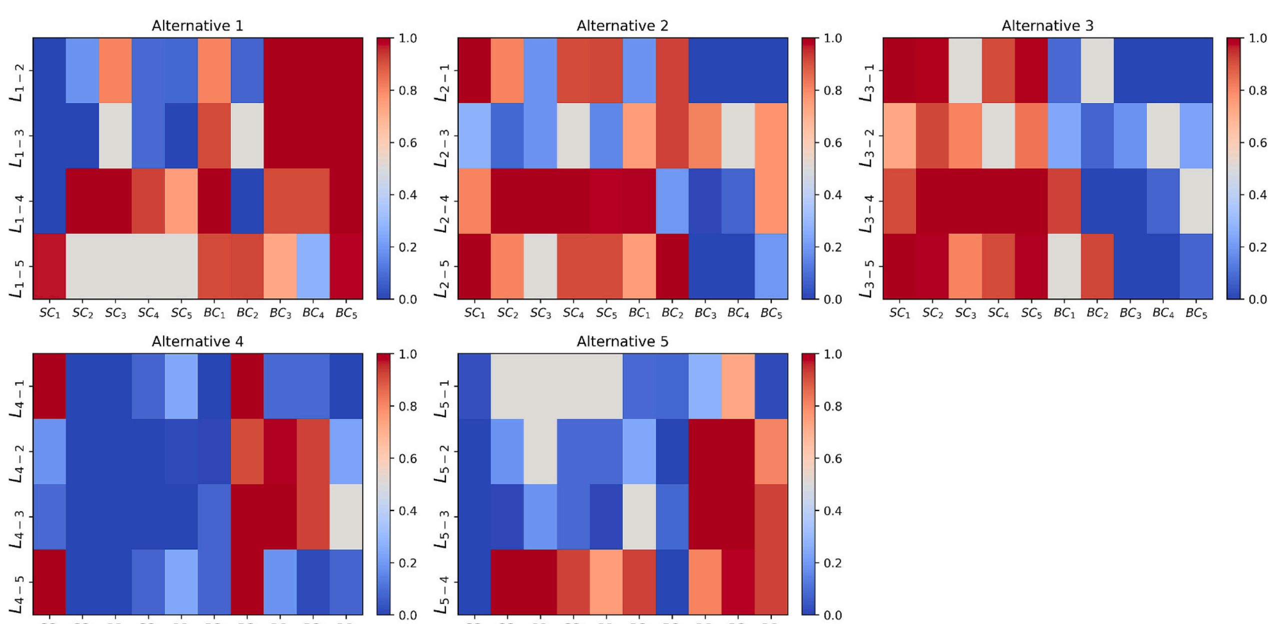

Fig. 7. Graphical presentation of the possibilities for five alternatives.

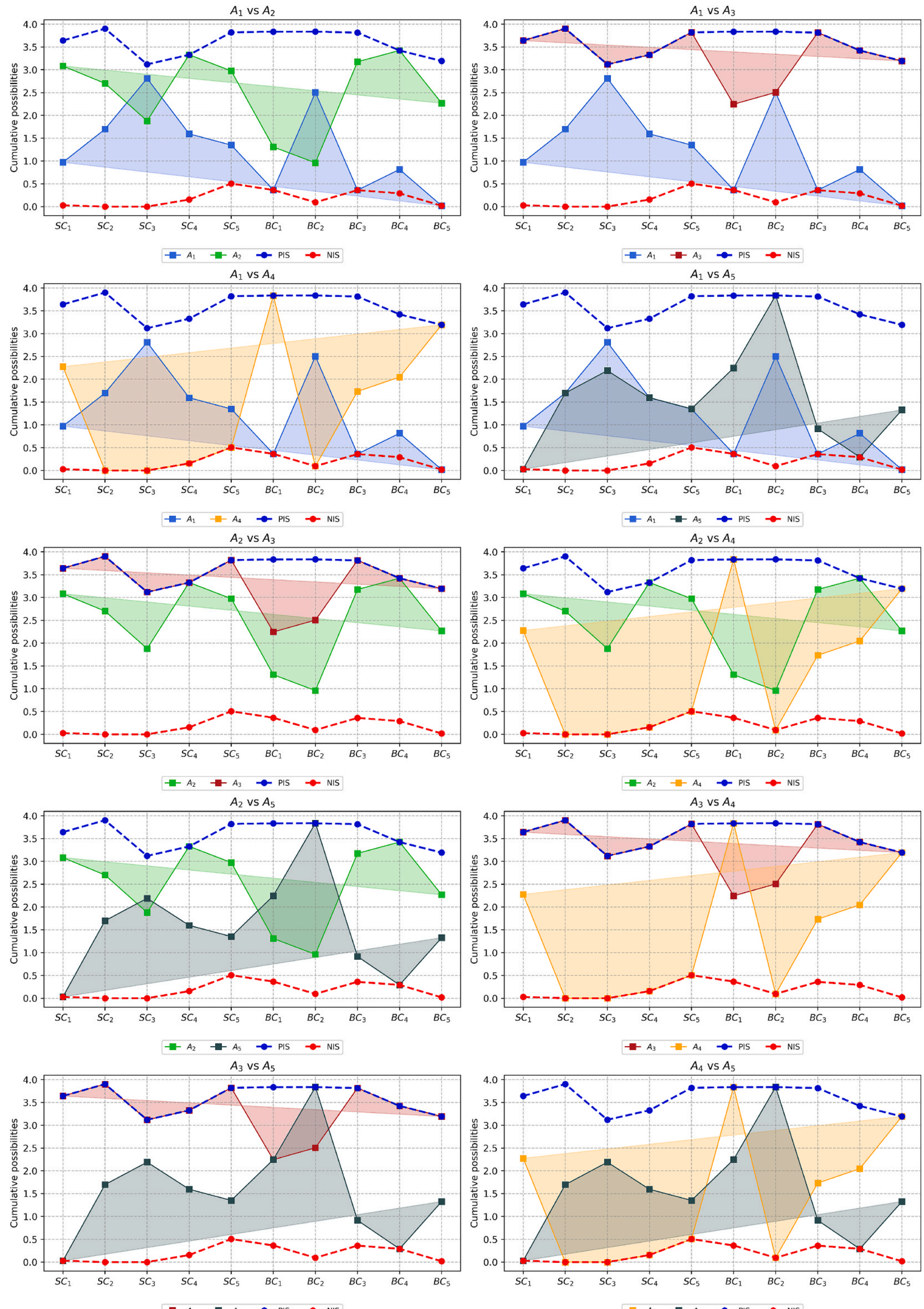

Fig. 8. Pairwise comparison of fuel alternatives.

the decision-making process by capturing uncertainty more comprehensively. Traditional IT2FS-based methods, such as IT2-VIKOR, IT2-ANP, and IT2-TOPSIS, aggregate fuzzy values without explicitly considering the range of possibilities associated with each alternative. In contrast, our proposed approach integrates possibility degrees, which represent the variability in expert opinions and provide a more detailed assessment of how each alternative performs across multiple criteria. By incorporating possibility degrees into the IT2F-VIKOR framework, we obtain a more nuanced ranking, particularly when alternatives exhibit similar performance levels. This explains why in the proposed case study, the ranking of A_4 and A_5 differs from conventional methods. Our approach reveals how their performances fluctuate under different possibility scenarios, whereas existing methods provide a more rigid ranking without fully capturing these variations. The ranking differences do not indicate a weakness but rather highlight the added value of the proposed method. The combination of possibility degrees and

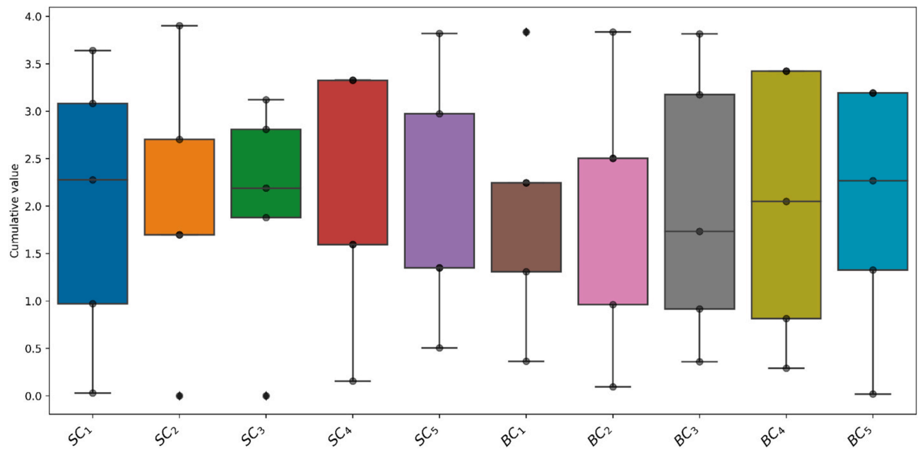

Fig. 9. The distribution of cumulative values $P_{\tilde{\psi}_j}$ for criteria.

VIKOR improves sensitivity to uncertainty, making the method particularly useful in complex decision-making scenarios where slight variations in evaluations can impact the final ranking. By incorporating possibility values, our approach offers a richer and more informative perspective on decision-making, allowing for a better understanding of how uncertainty influences rankings. Thus, despite the overall ranking consistency, minor deviations in the positions of A_4 and A_5 highlight the methodological differences inherent to the approaches and also the amount of uncertainty they can cover. These slight variations stem from the distinct mathematical foundations and computational processes of each method. Such differences underscore the significance of selecting an appropriate approach based on the specific context and decision-making requirements.

5. Results and discussion

In this section, the results of the illustrative case are analyzed. Most of the analyses are concluded based on the possibility-based VIKOR and the new decision matrix obtained according to the possibilities of alternatives.

Table 17
Sensitivity analysis of final rankings.

λ	χ_i					Final ranking
	A_1	A_2	A_3	A_4	A_5	
0.0	1.000	0.500	0.000	1.000	0.708	$A_3>A_2>A_5>A_4=A_1$
0.05	1.000	0.494	0.000	0.993	0.717	$A_3>A_2>A_5>A_4>A_1$
0.1	1.000	0.488	0.000	0.986	0.726	$A_3>A_2>A_5>A_4>A_1$
0.15	1.000	0.481	0.000	0.979	0.734	$A_3>A_2>A_5>A_4>A_1$
0.2	1.000	0.475	0.000	0.971	0.743	$A_3>A_2>A_5>A_4>A_1$
0.25	1.000	0.469	0.000	0.964	0.752	$A_3>A_2>A_5>A_4>A_1$
0.3	1.000	0.463	0.000	0.957	0.760	$A_3>A_2>A_5>A_4>A_1$
0.35	1.000	0.457	0.000	0.950	0.769	$A_3>A_2>A_5>A_4>A_1$
0.4	1.000	0.451	0.000	0.943	0.778	$A_3>A_2>A_5>A_4>A_1$
0.45	1.000	0.444	0.000	0.936	0.786	$A_3>A_2>A_5>A_4>A_1$
0.5	1.000	0.437	0.000	0.929	0.793	$A_3>A_2>A_5>A_4>A_1$
0.55	1.000	0.432	0.000	0.922	0.804	$A_3>A_2>A_5>A_4>A_1$
0.6	1.000	0.426	0.000	0.914	0.812	$A_3>A_2>A_5>A_4>A_1$
0.65	1.000	0.420	0.000	0.907	0.821	$A_3>A_2>A_5>A_4>A_1$
0.7	1.000	0.414	0.000	0.900	0.829	$A_3>A_2>A_5>A_4>A_1$
0.75	1.000	0.407	0.000	0.893	0.838	$A_3>A_2>A_5>A_4>A_1$
0.8	1.000	0.401	0.000	0.886	0.847	$A_3>A_2>A_5>A_4>A_1$
0.85	1.000	0.395	0.000	0.879	0.855	$A_3>A_2>A_5>A_4>A_1$
0.9	1.000	0.389	0.000	0.872	0.864	$A_3>A_2>A_5>A_4>A_1$
0.95	1.000	0.383	0.000	0.865	0.873	$A_3>A_2>A_4>A_5>A_1$
1.0	1.000	0.377	0.000	0.857	0.881	$A_3>A_2>A_4>A_5>A_1$

5.1. Analyses of renewable fuels

Fig. 7 represents a heatmap in which the x-axis represents all sustainability criteria and barriers. The y-axis, on the other hand, represents the possibility that alternative *i* outperforms other alternatives in response to criterion *j*. Each heatmap cell's color corresponds to the data value from Table 12. A visual reference for the values that the colors in the heatmap represent is provided by the color bar on the right side of the heatmap. The distribution of colors across several criteria and possibilities may be examined to interpret the heatmap's results. Higher values are shown by brighter cells, whereas lower values are indicated by darker cells. It can be observed which criterion or possibility has consistently high or low values, or if there are any clusters or gradients in the data. At first glance, it can be inferred that the bright cells are intensively dispersed around possibilities of alternative 2 and 3 for sustainability criteria, and darker cells are dispersed for barriers for these two alternatives, indicating that these two alternatives may outperform other alternatives. However, more calculations are required in order to obtain the exact ranking of these alternatives.

A pairwise comparison of five alternatives including "Advanced Biofuels," "Electricity," "Hydrogen," "1st Generation Biofuels," and "PtX Fuels" is also shown in Fig. 8. In this figure, spider plots are employed to show how each pair of alternatives perform across several criteria comparing to PIS and NIS. Each spider plot has two lines, one for each comparison alternative. The lines link the data points that indicate each alternative's performance values for the related criteria.

The performance profiles of the alternatives are represented by the shaded area between the lines and the PIS/NIS lines. The color coding is explained in the legend at the bottom of the plot. Every alternative has a unique color attached to it. A dashed blue line designates the PIS, while a dashed red line designates the NIS. By comparing the lines and shaded areas for different alternatives, can be observed as follows:

1) Advanced biofuels:

- Compared to 'Electricity': 'Advanced biofuels' tend to have lower overall performance values on most criteria except "Potential GHG Emission Reduction" and "Insufficient Technological & Market Infrastructures".
- Compared to 'Hydrogen': 'Advanced biofuels' often have lower performance numbers than 'Hydrogen' across the plot, except for "Insufficient Technological & Market Infrastructures" in which they both perform almost equally.
- Compared to '1st generation biofuels': In most criteria, "Advanced biofuels" outperform "1st generation biofuels" in terms of performance values, especially in the criteria related to sustainability.

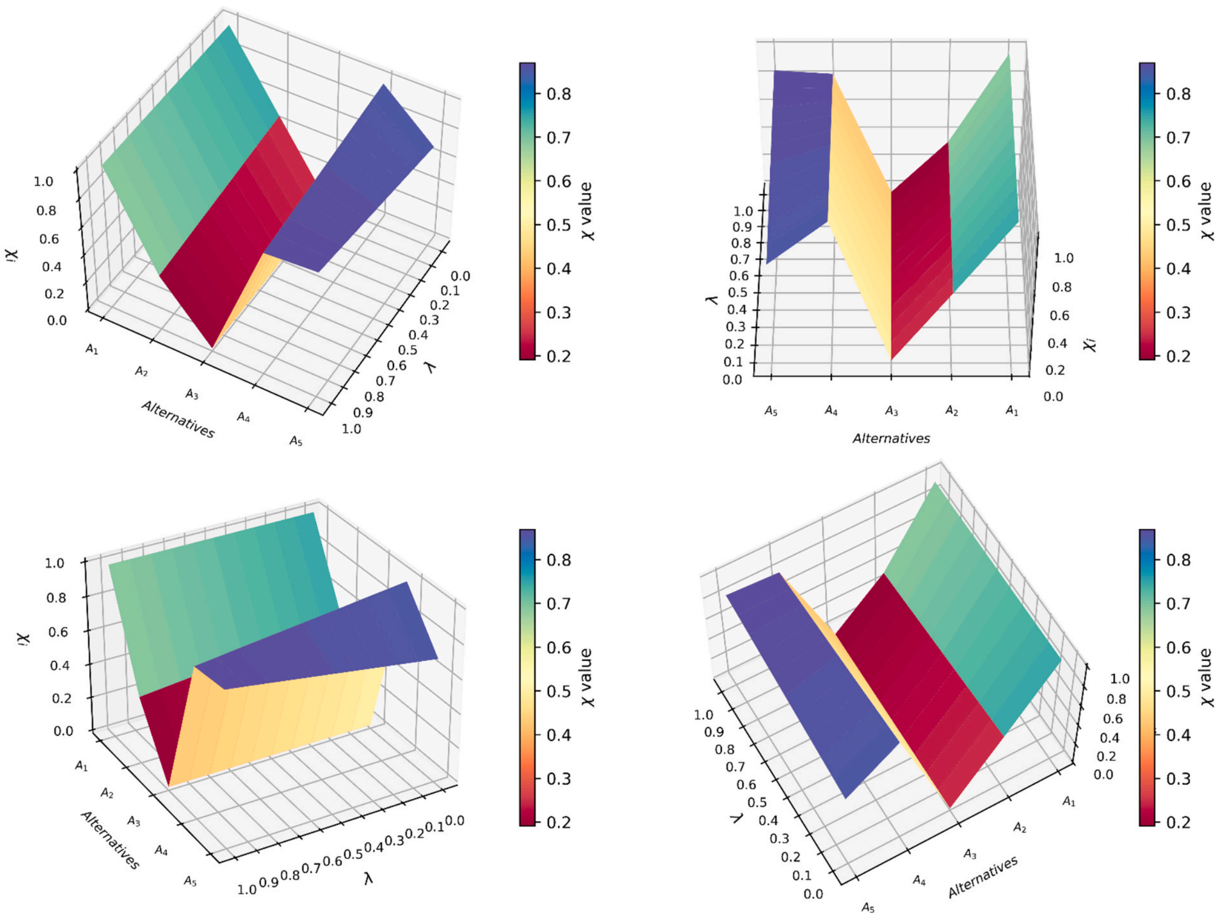

Fig. 10. Sensitivity analysis for final alternative rankings.

- Compared to 'PtX Fuels': 'Advanced biofuels' generally outperforms 'PtX Fuels' on most criteria except for "Promising Economic Benefits", "GHG Emissions" and "Lack of Feedstock (Raw Material) Availability".

2) Electricity:

- Compared to 'Hydrogen': 'Electricity' often has lower performance values than 'Hydrogen' across the plot.
- Compared to '1st generation biofuels': 'Electricity' outperforms "1st generation biofuels" in terms of performance values, except for "Lack of Public Acceptance" and "Short Travel Range" barriers.
- Compared to 'PtX Fuels': 'Electricity' also outperforms 'PtX Fuels' on most criteria except for "GHG Emissions", "Lack of Public Acceptance" and "Insufficient Technological & Market Infrastructures".

3) Hydrogen:

- Compared to '1st generation biofuels': 'Hydrogen' has higher performance values than '1st generation biofuels' except for "Lack of Public Acceptance" barrier.
- Compared to 'PtX Fuels': 'Hydrogen' performs significantly better than 'PtX Fuels' on most criteria except for "Insufficient Technological & Market Infrastructures" barrier.

4) 1st generation biofuels:

- Compared to 'PtX Fuels': '1st generation biofuels' performs lower than 'PtX Fuels' in most of sustainability criteria except for "Promising Economic Benefits". However, it outperforms 'PtX Fuels' in terms of barriers except for "Insufficient Technological & Market Infrastructures".

5) PtX Fuels:

- 'PtX Fuels' have already been compared with all the above fuels. However, it is notable that 'PtX Fuels' and '1st generation biofuels' perform similar in terms of distribution of data.

Fig. 9 represents the distribution of cumulative values $P_{\tilde{\tilde{\psi}}_j}$ for sustainability criteria and barriers derived from Table 13 in the shape of a boxplot. Every cumulative values, $P_{\tilde{\tilde{\psi}}_j}$ shows how alternatives behave differently in response to the associated criteria or barrier. The distribution of the data is represented graphically in the plot by boxplots for each criterion and barrier. The median value is shown by the line within each box, and the interquartile range is shown by the boxes in the figure. With the exception of outliers, which are displayed as separate points on the plot, the whiskers go to the minimum and maximum values. The plot also shows individual data points, shown as black circles, for each criterion or barrier. These points display the dataset's real values.

All of the boxplots for the barriers (Lack of Public Acceptance, Insufficient Technologies, Limited Policies, Lack of Feedstock, and Short Travel Range) and the majority of the sustainability criteria (Economic Benefits, Low Environmental & Ecological Footprints, High ratio of Employment & Job Creation, High Safety) have a symmetrical distribution with a median that is situated in the middle of the range. This implies that each category's data points are distributed equally.

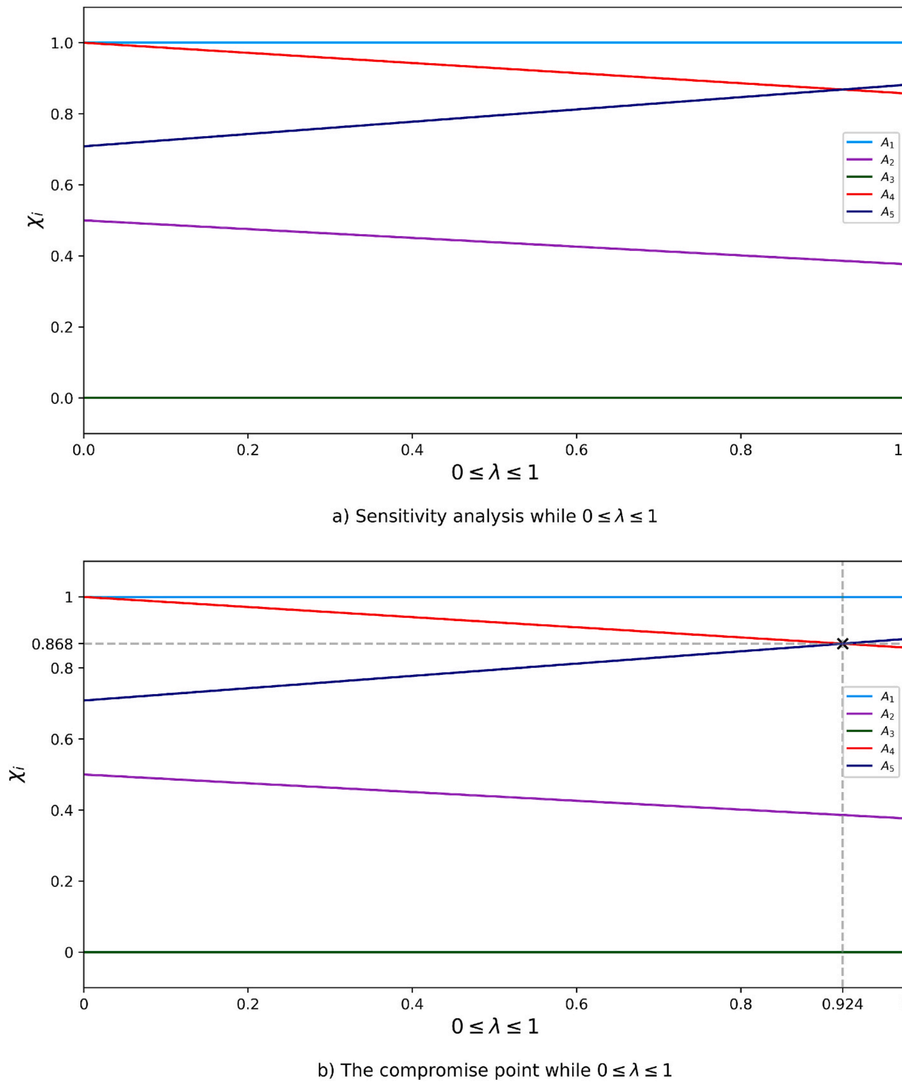

Fig. 11. Sensitivity analysis with the compromise point.

In comparison to the other criteria, the "GHG Reduction" boxplot differs somewhat in that its median is lower and its box length is shorter. This suggests that when compared to the other categories, "GHG Reduction" cumulative values are often lower, indicating that there is no significant difference in the performance of alternatives in response to "GHG Reduction".

The sustainability criteria "GHG Reduction" and "Job Creation" have considerably narrower interquartile ranges than other criteria and barriers in terms of variability. However, the interquartile ranges for the sustainability criterion "Low Environmental Footprints" and barrier "Insufficient Technologies" are wider, indicating that alternatives differ significantly in responding to these two factors.

5.2. Sensitivity analysis

A sensitivity analysis is conducted in this sub-section to reflect the changes in final ranking of alternatives in case of any change in the λ value (λ is a parameter that allows DMs to adjust the balance between the group utility measure S_i and the regret measure R_i in the final ranking). Table 17 shows the final rankings obtained for alternatives by changing the values of λ between the range of 0 and 1.

The 3D surface plot (Fig. 10) provides a clear visual representation of the relationship between the parameter λ, the alternatives, and their respective χ_i values. This plot uses three axes: the x-axis for λ values, the y-axis for the alternatives (A_1 to A_5), and the z-axis for the χ_i values. This multidimensional view allows for a comprehensive analysis of how each alternative's performance varies as λ changes. One of the key insights from the 3D surface plot is the invariance of A_3's χ_i value, which remains constant at 0.0 across all λ values. This confirms A_3's superiority and lack of dependence on the balance between the group utility measure (S_i) and the regret measure (R_i). Similarly, A_1's χ_i value remains at 1.0, signifying that it is unaffected by changes in λ, though it consistently performs the worst among all alternatives. In contrast, A_2, A_4, and A_5 demonstrate dynamic trends. A_2 and A_4 show decreasing χ_i values as λ increases, reflecting a decline in their relative performance. Notably, A_4's decline is steeper, highlighting a higher sensitivity to λ. On the other hand, A_5's χ_i value increases steadily, suggesting that its performance improves as the weight on the regret measure (R_i) grows. These trends are evident from the slopes and patterns on the surface plot, making it easy to identify each alternative's behavior in relation to λ. The visualization also allows decision-makers to explore the relationships between the alternatives from different angles. By rotating the plot or viewing it from distinct perspectives, it becomes evident how the χ_i values of the alternatives evolve and interact. For example, the visualization can highlight points of convergence or divergence between alternatives, aiding in the understanding of critical thresholds or intersection points.

The line plot (Fig. 11) provides a more detailed view of the χ_i values for each alternative as λ varies continuously across 500 incremental points. Unlike the 3D plot, which emphasizes overall patterns and interactions, the line plot focuses on specific trends and intersections, offering deeper insight into the sensitivity of rankings. The plot highlights the gradual decline in χ_i values for A_2 and A_4, with A_4 exhibiting a more pronounced drop. Conversely, A_5's χ_i value shows a consistent upward trend, indicating improved performance with higher values of λ. These trends underline the trade-offs involved in adjusting λ, where increasing the weight on R_i benefits some alternatives (e.g., A_5) while disadvantaging others (e.g., A_4). A key feature of this plot is the intersection point where A_4's and A_5's χ_i values converge at $\lambda \approx 0.925$. This marks a critical transition in the final rankings: for $\lambda < 0.925$, the rankings place A_5 above A_4, whereas for $\lambda > 0.925$, the order reverses, with A_4 overtaking A_5. Such intersection points are crucial in decision-making scenarios, as they indicate thresholds where small changes in λ can lead to significant shifts in outcomes. The line plot's granularity also reveals subtle differences in the sensitivity of each alternative to λ. For example, while both A_2 and A_4 decline with increasing λ, the slopes of their lines differ, indicating varying degrees of sensitivity. A_2's more gradual slope suggests greater stability compared to A_4, which might be relevant for decision-makers prioritizing robustness over performance.

The proposed possibility-based VIKOR approach has the following advantages:

- By the combination of IT2FS, the proposed method can effectively incorporate inherent uncertainty and vagueness in expert judgment data. Its effectiveness is beyond that of traditional VIKOR and other MCDM methods based on type-1 fuzzy sets or crisp data alone in capturing linguistic and subjective evaluations using oversimplification. Furthermore, decision outcomes are more reliable and accurate because the IT2FS approach captures more nuanced representations of expert preferences.
- In the traditional VIKOR, the method strongly relies on normalization in order to standardize the criteria values, which may bring biases and affect the final ranking of alternatives. The removal of the need for normalization is considered in the proposed method through constructing the decision matrix based on IT2FS possibilities. This innovation ensures that the rankings are unaffected due to the choice of various normalization techniques while ensuring robust and consistent results.
- The proposed method introduces the possibility-based decision matrix and uses pairwise comparisons that make it capable of distinguishing closely ranked alternatives. Such a capability is quite valuable in cases where small differences in performance might have a great impact on ranking with a view to correctly identifying the most optimal alternative.
- Unlike most of the existing methods of MCDM, this approach explicitly considers positive criteria-such as sustainability benefit-and negative criteria-such as barriers to market development-in an overall balanced way. This consideration makes for a more complete assessment of the alternatives, which better reflects real advantages and limitations.
- The approach will provide a possibility for the DMs to express their preferences in a more refined way, considering the possibility degree of each preference. It is so flexible that it will be applied almost on all kinds of decision problems having subjective data and imprecision. It is also a methodology quite well adapted to complex problems with several interacting criteria and alternatives, as underlined in the case study of renewable fuel selection. Besides, it integrates expert judgments with linguistic terms and differentiates between positive and negative criteria, which makes this a versatile tool for a wide range of decision-making domains.

5.3. Theoretical and managerial implications

The results obtained from this study contribute to the literature on MCDM by filling in the gaps on the application of fuzzy decision-making methods in renewable fuel selection with respect to freight transportation. Earlier studies employed MCDM approaches, such as traditional VIKOR, TOPSIS, and AHP, for the evaluation of alternatives based on a set of criteria. While a significant portion of these works lacks efficiency in handling uncertainties and impreciseness in expert judgment-particularly when those are linguistic, the proposed study develops the VIKOR by integrating advances in Fuzzy set theory in general, and IT2FS in particular, which address these challenges. The VIKOR approach that is being proposed will be more robust and accurate than other approaches for the evaluation of renewable fuel alternatives, using a possibility-based decision matrix and not including the normalization step. This follows indications in the literature for better handling of uncertainty.

The study further adds to the increasing literature on sustainability and energy transition in transport. Most of the available literature regarding renewable fuels identifies environmental advantages of alternative fuels with limited comprehensive assessment frames able to balance sustainability advantages with market development barriers. By including both positive criteria-such as economic benefits and GHG emission reduction-and negative ones-missing public acceptance and infrastructural limitations-this research develops a more holistic approach in the assessment of alternative fuels. This focus on duality addresses a literature gap, since most research has addressed these dimensions individually, resulting in incomplete fuel alternative evaluations. The findings highlight the importance of accounting for both the promise of renewable fuels and its challenges as one clear source of guidance directly relevant to real-world decision-making in the freight transportation sector.

The results have important implications in the selection of renewable fuels for aligning the renewable fuel targets of the European Union for 2030 and 2050. The ranking of hydrogen as the most feasible alternative, despite the drawbacks on infrastructure and public acceptance, also falls in line with the projection in the literature that green hydrogen has the potential to be a game-changer in transportation transformation. The call for the inclusion of advanced biofuels and PtX fuels is equally an indication that there is a diversified energy mix. A novelty in the work lies in the development of a framework that incorporates sustainability criteria with those of market barriers beyond the simple technical feasibility of renewable fuels to the consideration of how those fuels may actually be deployed, thus filling critical gaps in policy-relevant research.

The theoretical implications that are concluded by the proposed approach are listed below:

The Application of Interval Type-2 Fuzzy Sets (IT2FSs) in Decision Making: The research presents a unique method for incorporating IT2FSs into the VIKOR decision-making paradigm. This theoretical work is noteworthy because it bridges the gap between advanced fuzzy set theory (IT2FSs) and real decision-making procedures, allowing DMs to more effectively handle uncertainty.

Reducing Complexity in IT2FS Processing: This study tackles a typical issue when working with sophisticated IT2FSs: their complexity. The work offers an important contribution to easing the actual usage of these fuzzy sets by suggesting an approach to lessen the complexity of employing complex IT2FSs.

Normalization in VIKOR: When dealing with IT2FSs, the suggested approach eliminates the necessity for normalization in the VIKOR method. This theoretical addition is critical because it improves decision-making accuracy by eliminating the possible biases induced by normalization approaches in classic VIKOR models.

Adaptive Decision Modeling: The research extends the VIKOR approach to include possibilities of IT2FSs preference relations, allowing DMs to express their opinions more nuancedly. This flexibility in decision modeling is a key theoretical leap since it analyzes not just alternatives but also the degree of desire and possibility, resulting in more customized and realistic conclusions.

The proposed method also has some implications at the managerial level which are stated below:

Improved decision-making in difficult scenarios: With the addition of IT2FSs and possibilities, the proposed VIKOR model provides DMs with a more robust tool for dealing with difficult real-world scenarios. It allows for more informed judgments in cases where traditional VIKOR or fuzzy set techniques may fall short owing to their inability to deal with the complexities of uncertainty.

Enhanced sustainability assessment: The paper's approach provides for a more complete examination of alternative fuel alternatives in the context of the freight transportation problems. DMs may make more ecologically responsible and economically feasible decisions if they consider sustainability requirements as well as market development barriers at the same time.

Aggregation of expert judgements: The study recognizes the limits of depending on single expert evaluations and underlines the significance of aggregating judgements from several experts. This management contribution enables a more robust and trustworthy decision-making process by harnessing the combined experience of several experts.

6. Conclusion

In this study, a unique decision matrix is used to build a new possibility-based VIKOR model, which uses possibilities of interval type-2f fuzzy preference relations to resolve uncertainty. Despite the benefits of IT2FS over conventional type-1 fuzzy sets, processing sophisticated IT2FS in real-world applications is a recurring challenge for experts and DMs. Therefore, we developed a method that significantly decreases the challenge of employing complex IT2F sets. Experts' linguistic preferences have been utilized to explain the weights and performance for each specific alternative's position of priority. Possibilities of IT2FSs were used to create a new decision matrix once IT2FSs were fitted to these linguistic terms. Since the traditional VIKOR depends on converting the criterion values to a standard scale, the choice of the normalization method may affect the final rankings. The proposed possibility-based VIKOR is unique in the sense that it removes the normalization process of IT2FSs, making the results more accurate with a distinctive alternative ranking.

The proposed VIKOR approach is applied for an exemplary freight transportation problem related to alternative fuel selection, taking simultaneously into account sustainability factors and market development barriers. The present study seeks to combine judgments of several experts, since the conclusions obtained from a single expert are often inaccurate. Comparisons of the results with other methodologies supported the effectiveness and practicality of the proposed approach. In the case of freight transportation, five different alternatives have been evaluated based on ten criteria, out of which "Hydrogen" was ranked first when taking into account both sustainability and market barrier criteria. The pairwise comparison of the fuel alternatives also indicates that "Hydrogen" outperforms other alternatives from different perspectives except "Lack of Public Acceptance" and "Insufficient Technological & Market Infrastructures".

Contributions and novelty of the suggested approach may be deduced as follows when compared to all the prior approaches:

1) The proposed VIKOR model uses the advantages of possibilities derived from IT2FSs and hence is able to handle the intrinsic imprecision in the linguistic evaluation given by experts. Since they consider lower and upper membership functions, IT2FSs handle the uncertainty more fully than the traditional fuzzy set.
2) The extension of VIKOR includes development of a new decision matrix that makes the pairwise comparisons of the alternatives possible. Such a feature enables more precise evaluations, particularly when the differences among the alternatives are marginal, thus helping to determine the best choice. Unlike other methods that rely on the normalization process and depend directly on criteria weights and ratings, the proposed method suppresses normalization to arrive at more accurate rankings.
3) Decision modeling is more adaptable when using the extended VIKOR approach with possibilities of interval type-2 fuzzy sets. It enables DMs to express their preferences in a more nuanced manner by taking into account both the possibilities connected to each preference as well as the degree of desire. This may result in decisions that are more individualized and practical.
4) IT2FS possibilities integrated into the VIKOR framework reinforce further advance in decision science and fuzzy systems with new methods of handling uncertainty and imprecision in decision making. This new direction could thus position itself to inspire more researchers and further development in these fields.

While the proposed VIKOR approach shows significant enhancements in handling IT2FSs in terms of uncertainty and imprecision, it does have a few major shortcomings. Firstly, the computation of possibility within the IT2FSs imposes a computational burden that can become an issue for large-scale decision-making problems with a high number of criteria and alternatives; such problems may make the approach inapplicable to practitioners due to unavailability of the required computational resource or expertise. It also relies heavily on expert assessments in order to define the weights of the criteria and evaluate the performance of the alternatives. Incorporating multiple experts reduces bias, which, in turn, creates variability that can affect consistency, especially in cases where expert opinions diverge significantly. Third, the study is limited to only one application in freight transportation; though the approach can be generalized for a much larger class of problems, its efficacy has not been proved beyond that domain.

Future work may be conducted in order to overcome computational complexity of IT2FS possibility calculations with more efficient algorithms or by using machine learning or parallel processing. Other fuzzy set extensions such as spherical fuzzy sets, neutrosophic sets, and 2-tuple fuzzy sets may provide new ways toward the improvement of uncertainty handling and computational efficiency. Consequently, widening to renewable energy project selection, healthcare resource allocation, or even urban planning would be an important recognition of such a framework regarding its general applicability and robustness. Another direction could involve the use of more informative aggregation methods of expert judgment, for instance consensus building algorithms or weighted strategies concerning different levels of expertise in order to enhance coherence and reliability in the evaluations. For embedding dynamic decision capabilities to account for evolving criteria and integrated interactive tools through which DMs could iteratively adjust weights and rankings, expansion of practical utility and adaptability to real-world problems is performed.

Declaration of competing 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.

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Appendix

Table A1
The aggregated decision matrix from (K. Liu et al., 2018).

Alternatives	c_1	c_2	c_3
1	((0.7,0.9,0.95,1;1), (0.8,0.85,0.9,0.95;0.9))	((0.3,0.5,0.6,0.7;1), (0.4,0.5,0.55,0.6;0.9))	((0.5,0.7,0.8,0.9;1), (0.6,0.7,0.75,0.8;0.9))
2	((0.36,0.56,0.66,0.76;1), (0.46,0.56,0.61,0.66;0.9))	((0,0.37,0.50,0.62;1), (0.26,0.37,0.44,0.50;0.9))	((0,0.21,0.34,0.45;1), (0.13,0.20,0.27,0.34;0.9))
3	((0.56,0.76,0.85,0.93;1), (0.66,0.75,0.80,0.85;0.9))	((0.1,0.3,0.4,0.5;1), (0.2,0.3,0.35,0.4;0.9))	((0.36,0.56,0.66,0.76;1), (0.46,0.56,0.61,0.66;0.9))
4	((0.3,0.5,0.6,0.7;1), (0.4,0.5,0.55,0.6;0.9))	((0.7,0.9,0.95,1;1), (0.8,0.85,0.9,0.95;0.9))	((0.1,0.3,0.4,0.5;1), (0.2,0.3,0.35,0.4;0.9))
5	((0.5,0.7,0.8,0.9;1), (0.6,0.7,0.75,0.8;0.9))	((0.1,0.3,0.4,0.5;1), (0.2,0.3,0.35,0.4;0.9))	((0.40,0.61,0.70,0.79;1), (0.50,0.60,0.65,0.70;0.9))
Alternatives	c_4	c_5	c_6
1	((0.1,0.3,0.4,0.5;1), (0.2,0.3,0.35,0.4;0.9))	((0,0.29,0.42,0.53;1), (0.2,0.29,0.36,0.42;0.9))	((0.14,0.36,0.46,0.56;1), (0.25,0.36,0.41,0.46;0.9))
2	((0.37,0.62,0.71,0.79;1), (0.50,0.60,0.66,0.71;0.9))	((0.14,0.36,0.46,0.56;1), (0.25,0.36,0.41,0.46;0.9))	((0.5,0.7,0.8,0.9;1), (0.6,0.7,0.75,0.8;0.9))
3	((0.53,0.74,0.82,0.89;1), (0.63,0.71,0.76,0.82;0.9))	((0,0.37,0.50,0.62;1), (0.26,0.37,0.44,0.50;0.9))	((0,0.21,0.34,0.45;1), (0.13,0.20,0.27,0.34;0.9))
4	((0.5,0.7,0.8,0.9;1), (0.6,0.7,0.75,0.8;0.9))	((0,0.43,0.57,0.67;1), (0.32,0.42,0.50,0.57;0.9))	((0,0.19,0.32,0.43;1), (0.11,0.19,0.26,0.32;0.9))
5	((0,0.17,0.29,0.40;1), (0.1,0.17,0.23,0.29;0.9))	((0.7,0.9,0.95,1;1), (0.8,0.85,0.9,0.95;0.9))	((0,0.21,0.32,0.42;1), (0.13,0.21,0.26,0.32;0.9))
Alternatives	c_7	c_8	
1	((0,0.43,0.57,0.67;1), (0.32,0.42,0.50,0.57;0.9))	((0,0.21,0.34,0.45;1), (0.13,0.20,0.27,0.34;0.9))	
2	((0,0.29,0.42,0.53;1), (0.2,0.29,0.36,0.42;0.9))	((0,0.14,0.25,0.36;1), (0.08,0.14,0.20,0.25;0.9))	
3	((0.37,0.62,0.71,0.79;1), (0.50,0.60,0.66,0.71;0.9))	((0.14,0.36,0.46,0.56;1), (0.25,0.36,0.41,0.46;0.9))	
4	((0.3,0.5,0.6,0.7;1), (0.4,0.5,0.55,0.6;0.9))	((0,0.1,0.2,0.3;1), (0.05,0.1,0.15,0.2;0.9))	
5	((0.29,0.53,0.63,0.74;1), (0.42,0.53,0.58,0.63;0.9))	((0,0.19,0.32,0.43;1), (0.11,0.19,0.26,0.32;0.9))	

Data availability

No data was used for the research described in the article.

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