Evaluation of Climate Change-Resilient Transportation Alternatives Using Fuzzy Hamacher Aggregation Operators Based Group Decision-Making Model

Abstract

Climate change has become one of the most significant threats that all countries face. The extent of the effects of climate change will increase if the pace is not altered. Transportation systems are very important considering the order and organization of cities. Therefore, transportation networks must be resilient to the effects of climate change. In this study, three different alternatives to climate change resilient transportation networks, which are climate change resistant design of transportation facilities, alternative routes and strategies for the transportation systems, and climate preparedness, are defined. These alternatives are then assessed and prioritized under twelve sub-criteria using the decision-making model. By combining the interval-valued Fermatean fuzzy Hamacher aggregation operators with three decision-making methods termed the MEREC (method using the removal effects of criteria), RS (rank sum), and the MULTIMOORA (Multi-attribute Multi-Objective Optimization based on the Ratio Analysis), we develop a novel hybrid model for handling decision-making problems. The practicability and effectiveness of the presented model are tested with a case study. The results of the study show that operationally preparing for the effects of climate change is the best choice out of the ones that were given.

Keywords: Resilient transportation, Climate Change, Fermatean fuzzy set, Hamacher aggregation operators, MEREC, rank sum (RS), MULTIMOORA.

List of abbreviations	
List of abbreviations AF: Adaptation fund A-IVFF-DM: Aggregated interval-valued Fermatean fuzzy decision matrix AOs: Aggregation operators BG: Belongingness grade DE: Decision expert G: Good F: Fair FFS: Fermtean fuzzy set FMF: Full multiplicative form GHG: Greenhouse gas H: High IVFF: Interval-valued Fermatean fuzzy IVFFI: Interval-valued Fermatean fuzzy information IVFFN: Interval-valued Fermatean fuzzy number IVFFS: Interval-valued Fermatean fuzzy set IVFFHWA: Interval-valued Fermatean fuzzy Hamacher weighted averaging IVFFHWG: Interval-valued Fermatean fuzzy Hamacher weighted geometric IVFFS: Interval-valued Pythagorean fuzzy set IVFF-MEREC-RS-MULTIMOORA: Interval-Valued Fermatean Fuzzy-MEREC-RS-MULTIMOORA IVFF-NIS: Interval-valued Fermatean fuzzy positive Ideal solution IVFF-PIS: Interval-valued Fermatean fuzzy positive Ideal solution IVFFWA: Interval-valued Fermatean fuzzy weighted averaging IVFFWG: Interval-valued Fermatean fuzzy weighted geometric	IVFFHOWA: Interval-valued Fermatean fuzzy Hamacher ordered weighted average IVFFHOWA: Interval-valued Fermatean fuzzy Hamacher ordered weighted geometric IVFF-TOPSIS: Interval-valued Fermatean fuzzy technique for order of preference by similarity to an ideal solution IVFF-WSM: Interval-valued Fermatean fuzzy weighted sum model IVFF-WASPAS: Interval-valued Fermatean fuzzy weighted aggregated sum product assessment LRs: Linguistic ratings L: Low MCDM: Multi-criteria decision-making MEREC: MEthod based on the Removal Effects of Criteria MG: Moderate good ML: Moderate low MOORA: Multi-objective optimization by ratio analysis MULTIMOORA: Multiobjective optimization by ratio analysis plus full multiplicative form NG: Non-belongingness grade OAD: Overall assessment degree PG: Perfectly good PH: Perfectly high RPP: Reference point procedure RSP: Ratio system procedure SCBT: Sustainable community-based tourism TN: t-norm TC: t-conorm UNGCCC: United Nations framework convention on climate change VG: Very good VH: Very high VL: Very low VVL: Very very low

1. Introduction

Climate change has been affecting all living beings in many aspects, such as the increase in global temperatures, and rising sea levels (Malhi et al., 2021; Ghanbari et al., 2021). Findings indicate that there are both natural and anthropogenic causes of climate change (Stern and Kaufmann, 2013). Regardless of the causation, it is an undeniable fact that climate change has countless effects on all living beings. Precautions must be taken on each sector, such as transportation systems so that the negative effects of climate change can be limited and the resilience of these sectors to climate change can be increased. Operational disturbances on transportation networks related to climate change have the probability of increasing densities, queues, and traffic delays, which may reduce labor efficiency and increase the mental disturbances of the passengers (Ghorbanzadeh et al., 2021, Praharaj et al., 2021). Therefore, decision-makers need to adapt the transportation networks of cities to the changing conditions of the world, which is climate change in this case. In this study, three different alternative ways to increase the resilience of transportation networks to climate change are given and these alternatives are advantages prioritized by the assessments of the experts on the alternatives according to 12 different criteria. The uniqueness of the study is that a guide is constructed for decision-makers, who are considering going through a transition to adjust their transportation network to the conditions brought by climate change.

Going through the literature, there are many adverse effects of climate change on transportation networks. ~~In a~~ Different study~~, it is~~ stated that global temperature and sea level increases may have very negative effects on transportation networks soon (Zimmerman, 2003, Alabbad et al., 2021). Due to the rise in sea levels, it is expected that transportation networks close to sea levels are expected to face floods more often. Also, due to increasing global temperatures, the materials used in the construction of the networks are expected to have deteriorated (Lempert et al., 2021). Global warming and climate change have a directly proportional relationship with precipitation (Trenberth, 2011). As the temperatures increase, the vapor-carrying capacity of air increases, so droughts are expected to take place. However, as the water vapor in the air increases, precipitation events are likely to happen more severely. Therefore, seasonal floods related to precipitation events will be seen more often in the future, which may have adverse effects on transportation networks. In a book concerning the effects of climate change on the U.S. transportation, it is stated that with climate change, the intensity and frequency of hurricanes are expected to rise, which has an adverse effect on transportation (Transportation Research Board, 2008).

The potential effects given in the previous paragraph indicate that there is a significant need for increasing the resilience of transportation networks to climate change and making them more adaptable to changing conditions so that the operational and design aspects are not affected severely due to increasing temperatures, severe precipitation events, etc. In a study regarding the U.S. transportation facilities, new design standards are given, which aim to make the transportation network of the U.S. more resilient to the effects of climate change (Meyer, 2008). The design standards include subsurface conditions, material specifications, drainage, erosion, and location engineering. If the decision-makers comply with these design standards, the operational and design aspects of the transportation networks are considered to be resilient to the adverse impacts of climate change.

In this study, the applications that decision-makers can implement on the transportation networks are given under three alternatives. Since these alternatives are assessed according to twelve criteria, decision-makers can use the methodology of this study to make the advantage prioritization more adaptable to the geographical and cultural properties of the location. Thus, the most efficient way to make their transportation network resilient to the adverse effects of climate change can be selected, considering the characteristics of their location.

1.1. Research Motivations of the Study

Due to excessive GHG emissions all over the world, climate change has gained pace. Therefore, the resilience of sectors, such as transportation to the climate change subject, has become more important. The objective of this study is to constitute a guide for decision-makers ~~to use~~ while adjusting their transportation networks to become more resilient to climate change. Different alternatives are proposed and advantages prioritized so that decision-makers can be advised in the selection of the most suitable alternative.

Based on existing studies, we identify the research motivations behind this study, presented as

- In the theory of "interval-valued Fermatean fuzzy set (IVFFS)", both the degrees of belongingness and non-belongingness of an element is taken and presented in terms of interval values instead of real numbers, therefore, the IVFFS-based decision-making model provides more flexibility to deal with human evaluation. Due to its unique advantages, we present the proposed study under the IVFFS context.
- During the process of multi-criteria decision-making (MCDM), the consideration of "decision experts' (DEs')" weights is an important issue for the authors, however, these studies (Jeevaraj, 2021; Sergi et al., 2021; Rani and Mishra, 2022) have not considered the DEs' weights. Moreover, it is quite hard to assume the exact weight of the DE. Thus, to avoid the adverse influence of subjective DEs' significance on decision results, this study develops a formula for the determination of DEs' weights.
- To overcome the drawbacks of previous interval-valued Fermatean fuzzy aggregation operators (Jeevaraj, 2021; Sergi et al., 2021; Rani and Mishra, 2022; Rani et al., 2022), it

is essential to introduce novel aggregation operators for IVFFSs for managing "interval-valued Fermatean fuzzy information (IVFFI)".

- Few studies (Rani and Mishra, 2022; Rani et al., 2022) have determined the criteria weights from interval-valued Fermatean fuzzy perspectives. However, no study considers the objective and subjective criteria weight-determining models under an interval-valued Fermatean fuzzy environment. An integrated weighting model based on objective and subjective criteria weight-determining models can overcome the insufficiencies which arise either in an objective weight-determining model or a subjective weight-determining model. In this regard, we propose a new criteria weight-determining model, which can overcome the aforesaid limitations of existing studies.
- In comparison with existing IVFFI-based methods (Jeevaraj, 2021; Sergi et al., 2021; Rani and Mishra, 2022; Rani et al., 2022), the "multi-objective optimization by ratio analysis plus full multiplicative form (MULTIMOORA)" method has simple mathematical expressions, superior stability, less computational time and strength. Thus, to enhance the applicability and effectiveness of MULTIMOORA, we propose a hybrid MULTIMOORA method with objective and subjective weight-determining models under an interval-valued Fermatean fuzzy environment.

1.2. The Main Contributions of the Study

In this line, the prime contributions of this study are as follows:

- This study presents a novel hybrid decision-making methodology under an interval-valued Fermatean fuzzy environment.
- In this method, a new weight-determination formula is presented to compute the DEs weights from an interval-valued Fermatean fuzzy perspective.
- To avoid the limitations of existing interval-valued Fermatean fuzzy aggregation operators, some Hamacher operations-based aggregation operators including "interval-valued Fermatean fuzzy Hamacher weighted averaging (IVFFHWA)" and "interval-valued Fermatean fuzzy Hamacher weighted geometric (IVFFHWG)" operators are proposed and discussed.
- An integrated weight-determining process is developed to find the objective weights of criteria using the "method using the removal effects of criteria (MEREC)" and the subjective weights of criteria using the "rank sum (RS)" method.

- An extended MULTIMOORA method is proposed based on the combination of introduced aggregation operators and a new weight-determination procedure for treating the "multi-criteria decision making (MCDM)" problems with interval-valued Fermatean fuzzy information (IVFFI).
- An illustrative case study selection of resilient transportation networks against climate change alternatives is considered, proving the applicability and effectiveness of the presented method from the IVFFI perspective.
- A comparison with different methods is presented to illustrate the robustness of the obtained outcomes.
- Since authorities and decision-makers who want to make their transportation systems more climate resilient can vary the alternatives and criteria following their goals and application region, the study is highly adaptable.
- There is a scarcity of studies in the literature on the subject of alternatives, such as providing alternative routes and strategies for transportation systems and operationally preparing for the effects of climate change. As a result, in addition to the well-researched option of climate-resilient transportation facility design, this study suggests two novel climate-resilient transportation alternatives. All three choices are then advantage-prioritized, the outcome of this prioritization is critical in terms of guiding decision-makers.

This paper is structured as follows: Section 2 presents the overview of previous studies. In Section 3, the definition of the problem, the alternatives, and the criteria are given. Section 4 introduces an innovative MULTIMOORA method for MCDM problems. In Section 5, we implement the presented model in a case study of the alternative selection of climate-resistant transportation network decisions in a city. In addition, we discuss the comparison results. In Section 6, policy implications are given. In Section 7, a discussion on the results of the study is presented. Last, Section 8 presents the conclusion, limitations, and future research needs.

2. Literature Review

In this part of the study, we present the literature related to the present work.

2.1.Studies on Resilient Transport Network

Establishing a sustainable and resilient infrastructure system to protect the quality of human life in a period when natural resources are decreasing is important as it can provide optimization in socio-economic and environmental issues (Gopalakrishnan and Peeta, 2010). Transportation facilities play a significant role in supporting the national economy and social well-being and extreme events have caused terrible physical damage to the transportation infrastructure, with long-term socioeconomic effects (Dave et al., 2021). Much research focuses on the resilience of transportation infrastructure to support planning and design, as well as efficient management (Sun et al., 2020). The reason for the increasing interest in the resilience of transportation infrastructure is that infrastructure systems damaged in natural disasters today cause many serious socio-economic problems. To combat these increasing problems, a sustainable and flexible transportation infrastructure system should be established from the planning stage. Today, as people prefer to live in cities, sustainable urban life and development of the city depend on the level of service that the existing infrastructure services can provide. For this reason, it is important for city security to increase the durability and resilience levels of interrelated infrastructure systems such as transportation-electricity-energy-cyber systems and to design, monitor, and maintain them. (Havko et al., 2017). In research on reducing the impact of the transportation sector on climate change, which was carried out with the systematic literature review method by reviewing 153 papers, it was observed that with the development of public transportation systems, gains in environmental and public health could be achieved, and it was observed that public transportation vehicles emit 45% less CO2 than private vehicles (Jasim et al., 2021). The focus of attention in these studies is on technology and changes in human behavior and how this can be achieved (Kwan and Hashim, 2016). Because of the frequent climate change problems, disruptions occur in ports, railways, and highway systems, and these systems become vulnerable to disasters (Thaduri et al., 2021). For this reason, strategies have been developed by academics and were implemented in different regions (Wang et al., 2020). In the fight against these problems, first, the data should be shared transparently and used by researchers and managers. Institutions from different disciplines should work together because climate change is a multidisciplinary field and the transportation sector connects with many sectors. While experts on climate change and companies and managers serving in transportation should work together, the public should be educated to make them more conscious of the relationship between climate change and transportation preferences (Mills and Andrey, 2002).

2.2.Interval-valued Fermatean Fuzzy Set

In recent times, uncertain information becomes more and more diversified. However, in many practical decision processes, because of the fuzziness of evaluation information, the DEs always choose and express their information in terms of interval numbers within [0, 1] rather than the crisp values. In this respect, the notion of "Fermatean fuzzy set (FFS)" has been expanded to IVFFS (Rani and Mishra, 2022). The advantage of such an extended theory is that it represents uncertain information more closely to the DE's expectation. Sergi et al. (2021) studied a series of "aggregation operators (AOs)" for "interval-valued Fermatean fuzzy numbers (IVFFNs)". Further, Jeevaraj (2021) introduced several score functions for IVFFNs and studied their properties. Rani and Mishra (2022) proposed the score and accuracy functions for IVFFNs with their enviable properties. They suggested two AOs for aggregating the IVFFI and also, conferred some axioms.

2.3.Hamacher Aggregation Operator (AO)

The AO is a very imperative tool for treating MCDM problems. It is generally considered in terms of operational laws and functions. For operational laws, several AOs are particular cases of members in the "t-norm (TN)" and "t-conorm (TC)" families, and the Archimedean TN and TC are the generalized version of many TNs and TCs (Zhong et al., 2019). In the last few years, AOs have become a hot research issue (Liu and Wang, 2018). To aggregate the individual decision information, Hamacher (1978) presented the "Hamacher operations", which are good options for the *algebraic product and algebraic sum*, respectively. In the recent past, many research efforts have been done for different Hamacher operators with their relevance (Wei, 2019; Hadi et al., 2021). However, there is no study regarding the Hamacher operators for IVFFSs.

2.4.MULTIMOORA Method

In 2010, Brauers and Zavadskas (2010) pioneered a method, named *MULITIMOORA*, which is an extended version of the "multi-objective optimization by ratio analysis (MOORA)" approach, which adds a full multiplicative form for ranking. This method comprises three different evaluation models, which makes it one of the most robust and reliable approaches (Brauers and Zavadskas, 2010). The MULTIMOORA model is more viable for the assessment and prioritization of analogous complex problems (Hafezalkotob et al., 2019). Rani and Mishra (2021) presented Einstein operators-based MULTIMOORA model for the "electric vehicle charging station (EVCS)" selection. Baidya et al. (2021) developed bipolar complex fuzzy-based Archimedean power weighted operator-based -MULTIMOORA model to treat the third-party reverse logistics providers' selection problem. Chen et al. (2021) proposed an extended MULTIMOORA model to improve the accuracy of quality characteristics prioritization from a hesitant fuzzy linguistic perspective. Liu et al. (2021) gave the concept of intuitionistic linguistic rough MULTIMOORA technique for the assessment of sustainable suppliers. Saraji et al. (2021) discussed a combined hesitant fuzzy MULTIMOORA model in the analysis and assesses the challenges of adapting online education during the COVID-19 outbreak. He et al. (2021) initiated a decision-making model based on MULTIMOORA with “interval-valued Pythagorean fuzzy sets (IVPFSs)” to examine the current status of “sustainable community-based tourism (SCBT)” in the Indian Himalayan region context. In a recent study, Shang et al. (2022) suggested a hybridized fuzzy MULTIMOORA method for prioritizing sustainable suppliers. To evaluate the regional green development levels, Luo and Liu (2022) studied an improved MULTIMOORA approach with hesitant FFSs. However, no one has combined the MULTIMOORA method with IVFF-Hamacher AOs for climate change-resilient transportation alternatives evaluation.

3. Problem Definition

Climate change, which is one of the accepted facts in the 21st century, shows its effect more and more every year. Daily life can be adversely affected due to unpredictable precipitation and storms (Hsiao et al., 2021). Roads built according to traditional standardsmay have difficulties in adapting to current conditions. For this reason, the evaluation of the transportation facilities in terms of climate change and their design according to the specifications become inseparable from each other. Decision-makers create alternatives to reduce or even prevent the effects of negativities, especially in large cities, as the negativities to be experienced in traffic will adversely affect finance, psychology and the health of the people. Although these alternatives vary according to their location today, their existence has become a necessity (Jaroszweski et al., 2014).

3.1.Definition of Alternatives

The alternatives are defined as follows:

P_1: Climate change-resistant design of transportation facilities: In general, the roads are built in the strongest possible way within the necessary calculations, taking into account the climatic conditions of the region while the roads are being built. However, deviations in climate and weather caused by climate change may be beyond these calculations. Heavy rains that may be caused by climate change and landslides due to excessive rain can threaten transportation facilities. For this reason, it is important to build transportation networks that include climate change in the calculations, and this alternative has an important value in obtaining sustainable road networks against climate change (Meyer and Weigel, 2011).

P_2: Providing alternative routes and strategies for transportation systems: Transport facilities in cities may not always provide adequate results. The road may not be used in cases such as floods or soil subsidence. For this reason, the transport network needs to be rerouted. It is aimed at reducing the density of possible traffic demand by offering an alternative route or strategy to the drivers in the traffic. Therefore, this alternative aims to reorganize the traffic by offering different routes or strategies to the drivers (Markolf et al., 2019).

P_3: Preparing operationally for the impacts of climate change: Beyond the forecasts caused by climate change, storms, precipitation, etc. in natural events, many people in traffic may be affected. To prevent this situation, it may be necessary to consider the weather forecast reports or to provide the material and assistance for the drivers in that region to benefit from locations. In addition, in these cases, damages can be minimized by producing solutions against each scenario of the traffic network. Alternative 3 includes the preparation of all these operational activities (Markolf et al., 2019).

3.2.Definition of Criteria

Twelve decision criteria under four aspects are defined as follows:

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(1) Resilience aspect

Q_1: Vulnerability of the city life to extreme weather events (cost): Depending on climate change, it is expected that many vulnerable situations arise and may arise due to adverse weather in cities. The definition of vulnerability to climate change depends on 3 main headings, which are exposure level and duration, sensitivity to exposure, and adaptation status. When it is predicted that two-thirds of the human population will live in cities in 2050, it is predicted that situations that will create vulnerability to exposure levels will increase. At the root of these vulnerabilities is bad weather due to climate change, and research shows that flooding, heat waves, rainstorms, extreme heat, and drought are the most common problems. Especially in cities and regions with low-income populations, problems such as access to drinking water and flooding come to the fore (Wilby, 2007; McCarthy et. al., 2010; Gough et al., 2019).

Q_2: Transportation infrastructure failure (cost): When constructing transportation networks, transportation engineers frequently consult historical climate records, particularly extreme weather events. Bridges, for example, are frequently designed to withstand storms that occur once or twice

every 100 years. Historical climate; however, is no longer a good predictor of future danger due to climate change. Roads, automobiles, and trains will all be affected by climate change. The coating may soften and expand as the temperature rises. This can result in rutting and potholes, as well as increased stress on bridge joints, particularly in high-traffic locations. Heat waves can also impede construction activity, particularly in humidified locations (National Research Council (NRC), 2008).

Q_3: Impact on vehicles (cost): Many types of vehicles can overheat when the temperature rises and tires deteriorate more quickly. Milder winters, fewer cold days, later winter freezing, and earlier spring thaws, on the other hand, may lessen cold-weather damage to vehicles (USGCRP, 2014).

(2) Risk aspect

Q_4. Increased risk of delays in the transportation network (cost): Rails can expand and buckle as a result of high temperatures. To minimize derailments, more frequent and severe heat waves may necessitate track repairs or speed limitations. Heavy rains may cause delays and disruptions, while tropical storms and hurricanes may cause flooding or debris on trains, delaying rail travel and freight transit (Koetse and Rietveld, 2009).

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Q_5. Increased risk of disruptions in the transportation network (cost): Extreme events, such as storm surges, floods, and wind gusts, have a greater impact on transportation infrastructure and operations than small fluctuations in temperature or precipitation. In addition, transportation operations are more vulnerable to climate change than infrastructure. Sea level rise and storm surges are two threats that airports confront due to climate change, while high winds are a major hazard, especially when landing and taking off. Sea level rises, storm surges, floods, and high winds might all impede seaport operations. Floods that exceed the maximum permissible water levels and droughts that cause water levels to drop dangerously low, limiting navigation services, are examples of extreme weather phenomena that affect “inland waterways (IWW)” (Christodoulou and Demirel, 2018).

Q_6: Increased risk of damage and failure in the transportation network (cost): Rainfall will be concentrated into increasingly intense storms as a result of climate change. Flooding could occur as a result of heavy rainfall, disrupting traffic, delaying development, and weakening or washing out the soil and culverts that sustain roads, tunnels, and bridges. Bridges decay as soon as they are opened to traffic, but they are typically built to last more than 100 years. According to evidence, most existing bridges are working effectively without jeopardizing their safety when properly

maintained. According to a report, climate change has the potential to exert adverse effects on the safety, performance, and durability of bridges (Jaroszweski et al., 2010). Additionally, it is stated that in extreme conditions, some bridges may become unusable due to high temperatures, severe flood conditions, and so on.

(3) Economic aspect

Q_7: Maintenance cost of transportation facilities (cost): Road infrastructure in near-shore areas is especially vulnerable to more frequent flooding from sea level rise and storm surges. The pressure of water and snow can cause problems that require more frequent maintenance, repair, and rebuilding. The average service life of highways and roads is also shortened by flooding and heavy snow events. Therefore, the construction and maintenance of roads and highways may become costlier. Warmer winters can lead to reductions in salting requirements as well as snow and ice removal, resulting in reduced costs (NRC, 2008; USGCRP,2014).

Q_8: Financial resources integrated into national development plans for climate change (benefit): Climate finance, according to the "United Nations framework convention on climate change (UNFCCC)" standing committee on finance, is related to the finance used for diminishing GHG emissions and improving the resilience of human and ecological systems to adverse effects of climate change. The word has been used to refer to any financial flows related to climate change mitigation and adaptation, as well as shifting public resources from industrialized to developing nations in light of their UN climate convention responsibilities to provide financial resources that are new and additional (Reyes, 2013).

Q_9: External funds matching local needs for climate change research (benefit): To adapt to the negative effects of climate change and mitigate the consequences, significant financial resources are required. Supporting developing countries in building resilience to rising climate effects and spurring private sector climate investment is also crucial. Because direct government support is rare in many nations, climate finance is required to shift the global economy to a low-carbon path. The "green climate fund (GCF)" was formed to help disadvantaged societies adapt to the unavoidable effects of climate change by limiting or decreasing GHG emissions in developing countries. In 2001, the Kyoto protocol established the "adaptation fund (AF)", which has allocated US$532 million to climate adaptation and resilience programs (Buchner et al., 2011).

(4) The behavioral, political, and social aspect

Q_{10}. Political barriers to energy conservation (cost): In research, a barrier to energy efficiency refers to the prevention of a phenomenon that is sustainable and feasible in terms of energy and economy (Sorrell et al., 2004). Different research barriers are classified into three groups: 1) economic, 2) institutional, and 3) behavioral, which include social, cultural, and educational factors (Bagaini et. al., 2020). Economic constraints include challenges in obtaining credit, a lack of sufficient and reliable finance, and a significant risk for investors and financial institutions. Political blockage, inconsistent governance norms, and a lack of policy coordination are all examples of institutional impediments. Low consciousness of energy efficiency and non-energy benefits, a lack of knowledge or behavioral irregularities in processing information, a lack of trust, consumer attitude, and a way of living are all examples of behavioral obstacles (Langlois-Bertrand et al., 2015).

Q_{11}. Environmentally responsible behavior of the citizens (benefit): A citizen must help overcome any significant gaps or problems to build a sustainable society. Preparing people for environmental citizenship and sustainability education reveals similarities in some areas and disparities in others. Environmental citizenship; on the other hand, places a heavy priority on the environmental dimension of sustainability, as well as civic engagement in the private, social, and political spheres, within its definition. Environmental citizens can exercise their environmental rights and responsibilities, identifying the underlying structural reasons for environmental degradation and challenges, and addressing critical and active activities. They behave democratically, both individually and collectively, considering inter-and intra-generational fairness (Parra et al.,2015).

Q_{12}: Meeting the social expectation of the citizens (benefit): More successful strategies can be created by increasing determination and awareness by including human rights to involve the people more in the fight against climate change. The underlying motivation for this is the fundamental rights that all states are responsible to their citizens, and to ensure these fundamental rights, states must combat climate change. To ensure fundamental rights such as equality and non-discrimination, the problems that people living in different socio-economic regions will face due to climate change should be prevented. These disproportionate effects can be increased through cooperation in the fight against climate change (OHCHR, U., 2015).

4. Proposed Interval-Valued Fermatean Fuzzy-MEREC-RS-MULTIMOORA Method

In this section, we develop an integrated IVFF-MEREC-RS-MULTIMOORA method by combining the proposed interval-valued Fermatean fuzzy Hamacher AOs and MEREC and RS method to tackle the interval-valued Fermatean fuzzy MCDM problems. The details of IVFFSs and its related concepts are provided in Appendix A1. The procedural steps for IVFF-MEREC-RS-MULTIMOORA method are discussed as (see Fig. 1)

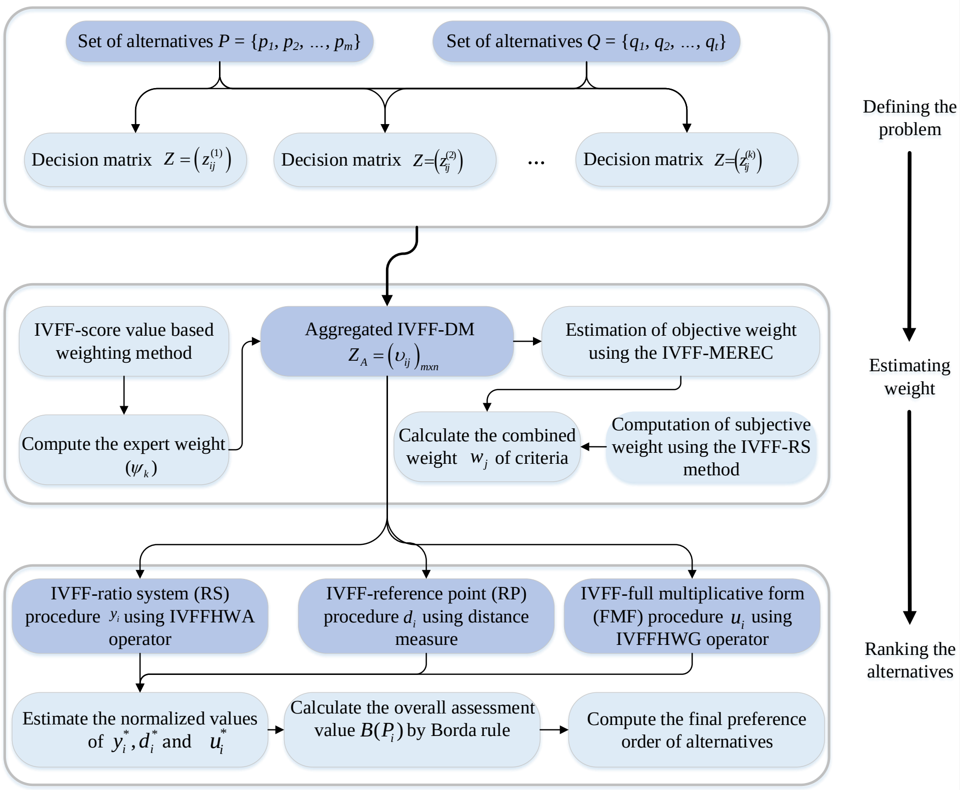

Fig. 1. The flowchart of IVFF-MEREC-RS-MULTIMOORA method.

Step 1: Construction of an "interval-valued Fermatean fuzzy decision matrix (IVFF-DM)".

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For a MCDM model, construct a set of alternatives $P=\{P_1, P_2, ..., P_s\}$ and classify the criteria set $Q=\{q_1, q_2, ..., q_t\}$. A set of DEs $D=\{D_1, D_2, ..., D_r\}$ evaluates the alternatives $P_i\left(i=1(1)s\right)$ in relation to a predefined set of criteria Q, in the form of "linguistic ratings (LRs)". As a result, we get r initial decision matrices $Z=\left(z_{ij}^{(\ell)}\right)$: $\ell=1, 2, ..., r$.

Step 2: Compute DEs' weights.

In this step, the weight of the ℓ^{th} expert is obtained by

$$\psi_\ell=\frac{\left(\mu_k^{lb}\right)^3\left(2-\left(\mu_k^{lb}\right)^3-\left(\nu_k^{lb}\right)^3\right)+\left(\mu_k^{ub}\right)^3\left(2-\left(\mu_k^{ub}\right)^3-\left(\nu_k^{ub}\right)^3\right)}{\sum_{\ell=1}^{r}\left(\left(\mu_k^{lb}\right)^3\left(2-\left(\mu_k^{lb}\right)^3-\left(\nu_k^{lb}\right)^3\right)+\left(\mu_k^{ub}\right)^3\left(2-\left(\mu_k^{ub}\right)^3-\left(\nu_k^{ub}\right)^3\right)\right)},\quad \ell=1,2,...,r. \qquad (1)$$

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Here, $\psi_\ell \geq 0$ and $\sum_{\ell=1}^{r}\psi_\ell=1$.

Step 3: Create the aggregated decision matrix.

To aggregate the individual opinions, the IVFFHWAO Eq. (A.9) is used to form $Z_A=\left[\upsilon_{ij}\right]_{s\times t}$, wherein $\upsilon_{ij}=\left(\left[\mu_{ij}^{lb}, \mu_{ij}^{ub}\right],\left[\nu_{ij}^{lb}, \nu_{ij}^{ub}\right]\right)$, $i=1,2,...,s,\ j=1,2,...,t$ be the "aggregated interval-valued Fermatean fuzzy decision matrix (A-IVFF-DM)", in which

$$\upsilon_{ij}=\left(\left[\sqrt[3]{\frac{\prod_{\ell=1}^{r}\left(1+(\varsigma-1)(\mu_{ij}^{lb})^3\right)^{\psi_\ell}-\prod_{\ell=1}^{r}\left(1-(\mu_{ij}^{lb})^3\right)^{\psi_\ell}}{\prod_{\ell=1}^{r}\left(1+(\varsigma-1)(\mu_{ij}^{lb})^3\right)^{\psi_\ell}+(\varsigma-1)\prod_{\ell=1}^{r}\left(1-(\mu_{ij}^{lb})^3\right)^{\psi_\ell}}}, \sqrt[3]{\frac{\prod_{\ell=1}^{r}\left(1+(\varsigma-1)(\mu_{ij}^{ub})^3\right)^{\psi_r}-\prod_{\ell=1}^{r}\left(1-(\mu_{ij}^{ub})^3\right)^{\psi_\ell}}{\prod_{\ell=1}^{r}\left(1+(\varsigma-1)(\mu_{ij}^{ub})^3\right)^{\psi_\ell}+(\varsigma-1)\prod_{\ell=1}^{r}\left(1-(\mu_{ij}^{ub})^3\right)^{\psi_\ell}}}\right],\right.$$

$$\left.\left[\frac{\sqrt[3]{\varsigma}\prod_{\ell=1}^{r}(\nu_{ij}^{lb})^{\psi_\ell}}{\sqrt[3]{\prod_{\ell=1}^{r}\left(1+(\varsigma-1)(1-(\nu_{ij}^{lb})^3)\right)^{\psi_\ell}+(\varsigma-1)\prod_{\ell=1}^{r}(\nu_{ij}^{lb})^{3\psi_\ell}}}, \frac{\sqrt[3]{\varsigma}\prod_{\ell=1}^{r}(\nu_{ij}^{ub})^{\psi_\ell}}{\sqrt[3]{\prod_{\ell=1}^{r}\left(1+(\varsigma-1)(1-(\nu_{ij}^{ub})^3)\right)^{\psi_\ell}+(\varsigma-1)\prod_{\ell=1}^{r}(\nu_{j}^{ub})^{3\psi_\ell}}}\right]\right). \qquad (2)$$

Step 4: Proposed IVFF-subjective and objective weighting integrated approach

Consider that each criterion has different significance. Consider that $w=\left(w_1, w_2, ..., w_t\right)^T$ be the weight vector of criterion set such that $\sum_{j=1}^{t}w_j=1$ and $w_j\in\left[0, 1\right]$. Here, we utilize the MEREC and RS methods for determining the criteria significance.

Case I: Determination of objective weights by the method of IVFF-MEREC.

The process for MEREC model is given in the following steps:

Step 4a: Normalization of the A-IVFF-DM.

Normalization procedure is performed by using Eq. (3), and thus, we obtain the normalized A-IVFF-DM $\square = \left(\varsigma_{ij}\right)_{s\times t}$,

$$\varsigma_{ij} = \left(\left[\bar{\mu}_{ij}^{lb}, \bar{\mu}_{ij}^{ub}\right], \left[\bar{\nu}_{ij}^{lb}, \bar{\nu}_{ij}^{ub}\right]\right) = \begin{cases} \upsilon_{ij} = \left(\left[\mu_{ij}^{lb}, \mu_{ij}^{ub}\right], \left[\nu_{ij}^{lb}, \nu_{ij}^{ub}\right]\right), & j \in Q_b, \\ \left(\upsilon_{ij}\right)^c = \left(\left[\nu_{ij}^{lb}, \nu_{ij}^{ub}\right], \left[\mu_{ij}^{lb}, \mu_{ij}^{ub}\right]\right), & j \in Q_n. \end{cases} \tag{3}$$

where ς_{ij} denotes the normalized IVFFN, and Q_b and Q_n denote the benefit and cost criterion, respectively.

Step 4b: Computation of the score matrix.

By means of the score value given by (Rani and Mishra, 2022), compute the score matrix $\Omega = \left(\eta_{ij}\right)_{s\times t}$ of each IVFFN ς_{ij}, where

$$\eta_{ij} = \frac{1}{2}\left(\left(\frac{1}{2}\left((\mu_{ij}^{lb})^3 + (\mu_{ij}^{ub})^3 - (\nu_{ij}^{lb})^3 - (\nu_{ij}^{ub})^3\right)\right) + 1\right), \tag{4}$$

where η_{ij} denotes the score value of each IVFFN ς_{ij}.

Step 4c: Calculation of overall performance of the alternatives.

Corresponding to the Keshavarz-Ghorabaee et al., (2021) and Rani et al., (2021), the overall performance (S_i) of each alternative is computed using Eq. (5),

$$S_i = ln\left(1 + \left(\frac{1}{t}\sum_j \left|ln\left(\eta_{ij}\right)\right|\right)\right). \tag{5}$$

Step 4d: Computation of the performance of the alternatives by removal of each criterion.

In this step, the performances of alternatives are computed by removal of each criterion independently. Thus, we obtain '*t*' sets of performances related to '*t*' criteria. In the following, we compute the performance of *i*th alternative by removing the jth criterion, denoted by S'_{ij}:

$$S'_{ij} = ln\left(1+\left(\frac{1}{n}\sum_{k,k\neq j}\left|ln\left(\eta_{ik}\right)\right|\right)\right). \tag{6}$$

Step 4e: Find the sum of absolute deviations.

With the use of Eq. (7), we compute the sum of absolute deviations (U_j), which as

$$U_j = \sum_i \left|S'_{ij} - S_i\right|. \tag{7}$$

Step 4f: Estimate the weights of criteria.

The expression is utilized for the calculation of w_j^M as follows:

$$w_j^M = \frac{U_j}{\sum_{j=1}^{t} U_j}, \tag{8}$$

where w_j^M denotes the objective weight of j^{th} criterion, where j=1,2,…,t.

Case II: Determine the subjective weights by IVFF-rank sum (RS) method

The subjective weight-determining process allows to reflect the views and intrinsic values of the decision-making experts. In the MCDM procedure, the views of decision-making experts for each alternative concerning the criteria play an imperative role in the selection of optimum candidate (Stillwell et al, 1981; Narayanamoorthy et al., 2020). In the following, the subjective weight-determining formula for rank-sum weight method is presented:

$$w_j^R = \frac{t - m_p + 1}{\sum_{j=1}^{t}\left(t - m_p + 1\right)}, \tag{9}$$

where w_j^R denotes the subjective weight of the j^{th} criterion $\left(j = 1, 2, ..., t\right)$ and m_p denotes the rank of each criterion.

Case III: Integrated weights using the proposed weighting method

In A-IVFF-DM, the decision-making experts want to employ both the objective and subjective weighting methods, for this purpose, Eq. (10) is utilized. Thus, the combined weighting formula is given as

$$w_j = \tau w_j^M + (1-\tau) w_j^R, \tag{10}$$

where $\tau \in [0, 1]$ is an objective factor of A-IVFF-DM weights.

Step 5: By means of "ratio system procedure (RSP)", determine the ranking of the options.
This step involves the following procedures:

Step 5.1: Based on benefit and cost criteria, find the significance values Y_i^+ and Y_i^- of each alternative using the IVFFHWAO, defined by Eq. (A.9) in Appendix A1 as

$$Y_i^+ = \left(\left[\sqrt[3]{\frac{\prod_{j\in Q_b}\left(1+(\varsigma-1)(\mu_{ij}^{lb})^3\right)^{w_j} - \prod_{j\in Q_b}\left(1-(\mu_{ij}^{lb})^3\right)^{w_j}}{\prod_{j\in Q_b}\left(1+(\varsigma-1)(\mu_{ij}^{lb})^3\right)^{w_j} + (\varsigma-1)\prod_{j\in Q_b}\left(1-(\mu_{ij}^{lb})^3\right)^{w_j}}}, \sqrt[3]{\frac{\prod_{j\in Q_b}\left(1+(\varsigma-1)(\mu_{ij}^{ub})^3\right)^{w_j} - \prod_{j\in Q_b}\left(1-(\mu_{ij}^{ub})^3\right)^{w_j}}{\prod_{j\in Q_b}\left(1+(\varsigma-1)(\mu_{ij}^{ub})^3\right)^{w_j} + (\varsigma-1)\prod_{j\in Q_b}\left(1-(\mu_{ij}^{ub})^3\right)^{w_j}}} \right], \right.$$
$$\left. \left[\frac{\sqrt[3]{\varsigma}\prod_{j\in Q_b}(\nu_{ij}^{lb})^{w_j}}{\sqrt[3]{\prod_{j\in Q_b}\left(1+(\varsigma-1)(1-(\nu_{ij}^{lb})^3)\right)^{w_j} + (\varsigma-1)\prod_{j\in Q_b}(\nu_{ij}^{lb})^{3w_j}}}, \frac{\sqrt[3]{\varsigma}\prod_{j\in Q_b}(\nu_{ij}^{ub})^{w_j}}{\sqrt[3]{\prod_{j\in Q_b}\left(1+(\varsigma-1)(1-(\nu_{ij}^{ub})^3)\right)^{w_j} + (\varsigma-1)\prod_{j\in Q_b}(\nu_{j}^{ub})^{3w_j}}} \right] \right). \tag{11}$$

$$Y_i^- = \left(\left[\sqrt[3]{\frac{\prod_{j\in Q_n}\left(1+(\varsigma-1)(\mu_{ij}^{lb})^3\right)^{w_j} - \prod_{j\in Q_n}\left(1-(\mu_{ij}^{lb})^3\right)^{w_j}}{\prod_{j\in Q_n}\left(1+(\varsigma-1)(\mu_{ij}^{lb})^3\right)^{w_j} + (\varsigma-1)\prod_{j\in Q_n}\left(1-(\mu_{ij}^{lb})^3\right)^{w_j}}}, \sqrt[3]{\frac{\prod_{j\in Q_n}\left(1+(\varsigma-1)(\mu_{ij}^{ub})^3\right)^{w_j} - \prod_{j\in Q_n}\left(1-(\mu_{ij}^{ub})^3\right)^{w_j}}{\prod_{j\in Q_n}\left(1+(\varsigma-1)(\mu_{ij}^{ub})^3\right)^{w_j} + (\varsigma-1)\prod_{j\in Q_n}\left(1-(\mu_{ij}^{ub})^3\right)^{w_j}}} \right], \right.$$
$$\left. \left[\frac{\sqrt[3]{\varsigma}\prod_{j\in Q_n}(\nu_{ij}^{lb})^{w_j}}{\sqrt[3]{\prod_{j\in Q_n}\left(1+(\varsigma-1)(1-(\nu_{ij}^{lb})^3)\right)^{w_j} + (\varsigma-1)\prod_{j\in Q_n}(\nu_{ij}^{lb})^{3w_j}}}, \frac{\sqrt[3]{\varsigma}\prod_{j\in Q_n}(\nu_{ij}^{ub})^{w_j}}{\sqrt[3]{\prod_{j\in Q_n}\left(1+(\varsigma-1)(1-(\nu_{ij}^{ub})^3)\right)^{w_j} + (\varsigma-1)\prod_{j\in Q_n}(\nu_{j}^{ub})^{3w_j}}} \right] \right). \tag{12}$$

where Q_b and Q_n denote the benefit and cost criterion, respectively.

Step 5.2: In the following, we determine the score values of significance values Y_i^+ and Y_i^-:

$$k_i^+ = \mathrm{S}\left(Y_i^+\right) \text{ and } k_i^- = \mathrm{S}\left(Y_i^-\right). \tag{13}$$

Step 5.3: Estimate the assessment degree (k_i) of each alternative

$$k_i = k_i^+ - k_i^- . \tag{14}$$

Step 5.4: Prioritize the alternatives and then select the optimal one. The priority order of alternatives is obtained using the RSP.

Step 6: By means of “reference point procedure (RPP)”, determine the ranking of the options. This process involves the following steps:

Step 6.1: By utilizing Eq. (15), calculate each coordinate of the “reference point (RP)” $f^* = \{f_1^*, f_2^*, ..., f_t^*\}$, where f_j^* is an IVFFN.

$$f_j^* = \begin{cases} \left(\left[\max_i \mu_{ij}^{lb}, \max_i \mu_{ij}^{ub}\right], \left[\min_i \nu_{ij}^{lb}, \min_i \nu_{ij}^{ub}\right]\right), \text{ for benefit criterion } Q_b \\ \left(\left[\max_i \nu_{ij}^{lb}, \max_i \nu_{ij}^{ub}\right]\left[\min_i \mu_{ij}^{lb}, \min_i \mu_{ij}^{ub}\right]\right), \text{ for cost criterion } Q_n \end{cases}. \tag{15}$$

Step 6.2: Determine the divergence from each alternative to all ratings of the RP, shown as

$$D_{ij} = w_j \left(D\left(\upsilon_{ij}, f_j^*\right)\right), \tag{16}$$

where D_{ij} shows the divergence of i^{th} alternative P_i, given by Eq. (A.7) in Appendix A1.

Step 6.3: By means of Eq. (17), estimate the maximum divergence (d_i) of each candidate.

$$d_i = \max_j D_{ij};\ i = 1, 2, ..., s. \tag{17}$$

Step 6.4: Rank the alternatives and then opt the most appropriate one.

Step 7: By means of FMF, determine the ranking of the options.
This step contains the following processes:

Step 7.1: Find the values of A_i and B_i using the IVFFHWGO, defined by Eq. (A.13) in Appendix A1 as

$$A_i = \left(\left[\frac{\sqrt[3]{\varsigma}\prod_{j\in Q_b}(\mu_{ij}^{lb})^{w_j}}{\sqrt[3]{\prod_{j\in Q_b}\left(1+(\varsigma-1)(1-(\mu_{ij}^{lb})^3)\right)^{w_j}+(\varsigma-1)\prod_{j\in Q_b}(\mu_{ij}^{lb})^{3w_j}}}, \frac{\sqrt[3]{\varsigma}\prod_{j\in Q_b}(\mu_{ij}^{lb})^{w_j}}{\sqrt[3]{\prod_{j\in Q_b}\left(1+(\varsigma-1)(1-(\mu_{ij}^{lb})^3)\right)^{w_j}+(\varsigma-1)\prod_{j\in Q_b}(\mu_{ij}^{lb})^{3w_j}}}\right], \tag{18}$$

$$\left[\sqrt[3]{\frac{\prod_{j\in Q_b}\left(1+(\varsigma-1)(v_{ij}^{lb})^3\right)^{w_j}-\prod_{j\in Q_b}\left(1-(v_{ij}^{lb})^3\right)^{w_j}}{\prod_{j\in Q_b}\left(1+(\varsigma-1)(v_{ij}^{lb})^3\right)^{w_j}+(\varsigma-1)\prod_{j\in Q_b}\left(1-(v_{ij}^{lb})^3\right)^{w_j}}},\sqrt[3]{\frac{\prod_{j\in Q_b}\left(1+(\varsigma-1)(v_{ij}^{ub})^3\right)^{w_j}-\prod_{j\in Q_b}\left(1-(v_{ij}^{ub})^3\right)^{w_j}}{\prod_{j\in Q_b}\left(1+(\varsigma-1)(v_{ij}^{ub})^3\right)^{w_j}+(\varsigma-1)\prod_{j\in Q_b}\left(1-(v_{ij}^{ub})^3\right)^{w_j}}}\right]\Bigg),$$

$$B_i=\left(\left[\frac{\sqrt[3]{\varsigma}\prod_{j\in Q_n}(\mu_{ij}^{lb})^{w_j}}{\sqrt[3]{\prod_{j\in Q_n}\left(1+(\varsigma-1)(1-(\mu_{ij}^{lb})^3)\right)^{w_j}+(\varsigma-1)\prod_{j\in Q_n}(\mu_{ij}^{lb})^{3w_j}}},\frac{\sqrt[3]{\varsigma}\prod_{j\in Q_n}(\mu_{ij}^{lb})^{w_j}}{\sqrt[3]{\prod_{j\in Q_n}\left(1+(\varsigma-1)(1-(\mu_{ij}^{lb})^3)\right)^{w_j}+(\varsigma-1)\prod_{j\in Q_n}(\mu_{ij}^{lb})^{3w_j}}}\right],\right. \tag{19}$$

$$\left.\left[\sqrt[3]{\frac{\prod_{j\in Q_b}\left(1+(\varsigma-1)(v_{ij}^{lb})^3\right)^{w_j}-\prod_{j\in Q_b}\left(1-(v_{ij}^{lb})^3\right)^{w_j}}{\prod_{j\in Q_b}\left(1+(\varsigma-1)(v_{ij}^{lb})^3\right)^{w_j}+(\varsigma-1)\prod_{j\in Q_b}\left(1-(v_{ij}^{lb})^3\right)^{w_j}}},\sqrt[3]{\frac{\prod_{j\in Q_b}\left(1+(\varsigma-1)(v_{ij}^{ub})^3\right)^{w_j}-\prod_{j\in Q_b}\left(1-(v_{ij}^{ub})^3\right)^{w_j}}{\prod_{j\in Q_b}\left(1+(\varsigma-1)(v_{ij}^{ub})^3\right)^{w_j}+(\varsigma-1)\prod_{j\in Q_b}\left(1-(v_{ij}^{ub})^3\right)^{w_j}}}\right]\right).$$

where A_i and B_i are IVFFNs, and Q_b and Q_n denote the benefit and cost criterion, respectively.

Step 7.2: Obtain the score values of A_i and B_i, given by

$$\varsigma_i = \mathrm{S}(A_i) \text{ and } \tau_i = \mathrm{S}(B_i). \tag{20}$$

Step 7.3: With the use of Eq. (21), compute the utility (u_i) for each alternative, which as

$$u_i = \frac{\varsigma_i}{\tau_i}. \tag{21}$$

Step 7.4: Prioritize the alternatives and then choose the most appropriate one.

Step 8: Determine the overall priority order of the alternatives.

By means of vector normalization, firstly normalize the RSP, RPP and FMF scores of the alternatives. Based on Modified Borda Rule, the "overall assessment degree (OAD)" of i^{th} alternative is given by Eq. (22),

$$B(P_i)=k_i^*\cdot\frac{s-\rho\left(k_i^*\right)+1}{\left(s\left(s+1\right)/2\right)}-d_i^*\cdot\frac{\rho\left(d_i^*\right)}{\left(s\left(s+1\right)/2\right)}+u_i^*\cdot\frac{s-\rho\left(u_i^*\right)+1}{\left(s\left(s+1\right)/2\right)};\ i=1,2,...,s. \tag{22}$$

where $k_i^*=\frac{k_i}{\sqrt{\sum_{i=1}^{s}\left(k_i\right)^2}}$, $d_i^*=\frac{d_i}{\sqrt{\sum_{i=1}^{s}\left(d_i\right)^2}}$, $u_i^*=\frac{u_i}{\sqrt{\sum_{i=1}^{s}\left(u_i\right)^2}}$, and $\rho\left(k_i^*\right)$, $\rho\left(d_i^*\right)$ and $\rho\left(u_i^*\right)$ are the ranking sets of RSP, RPP and FMF, correspondingly. The most suitable candidate has the utmost value of $B\left(P_i\right)$.

5. Results

This research focuses on the implementation of the proposed methodology for sustainable and efficient, resilient transport network alternatives. To understand the importance of the alternatives and criteria in the research, an imaginary densely populated metropolitan city, developed in terms of transportation networks, with heavy traffic demands and where the impact of climate change is intense, has been considered. The determination of the most effective solution for the city by the decision-makers is needed not only economically but also in terms of traffic demand and problems. To carry out the questionnaire in the most optimal way, the selected experts must have both theoretical and practical knowledge about the cities in this condition. Therefore, 3 different alternatives are determined and evaluated in terms of 12 sub-criteria.

5.1. Sensitivity Analysis

This subsection shows sensitivity investigation associated with the parameter τ. The variation of τ is a useful issue helping to evaluate the sensitivity level of the approach, changing from subjective weighting values to the objective weighting values of criteria to assess the overall assessment degree and preference order. In addition, changing the values of τ is applied to the investigation of the sensitivity of the proposed method to the eminence of attribute weights.

Commented [ZY7]: This is the first table that appears.

Table 1 and Fig. ~~3~~ 2 represent the sensitivity analysis of the options for diverse values of the utility parameter τ. Based on the assessments, we obtain similar preferences $P_3 \succ P_1 \succ P_2$ for each value of τ, which implies P_3 is at the top of the ranking for each value of τ, while P_2 has the last rank for each value of τ. Therefore, it is observable that the developed method possesses adequate stability with numerous parameter values. As shown clearly in Table 1, the developed IVFF-MEREC-RS-MULTIMOORA methodology is capable of generating stable and, at the same time, flexible preference results in a variety of utility parameters. This property is of high importance for MCDM procedures and decision-making reality.

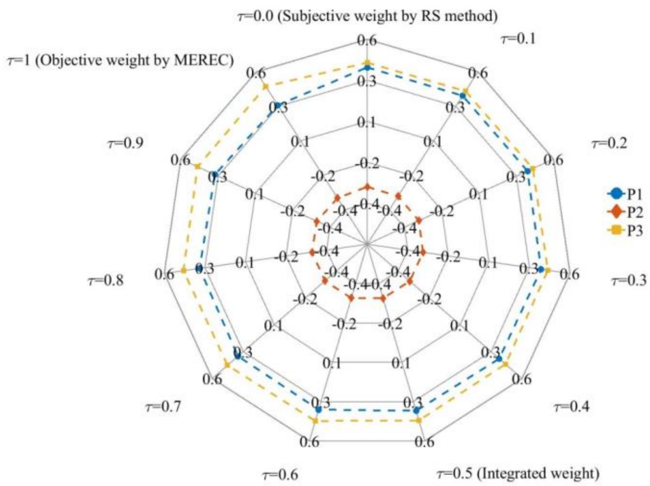


Fig. 2 Sensitivity outcomes of the $B(P_i)$ values over the utility parameter τ

Commented [ZY8]: The sequence is incorrect. Figure 2 is the correct order.

Table 1
Ranking results of the IVFF-MEREC-RS-MULTIMOORA method with different values of *τ*.

T	P_1	P_2	P_3	Ranking order
0.0 (Subjective weight by RS method)	0.4286	-0.2999	0.4574	$P_3 \succ P_1 \succ P_2$
0.1	0.4268	-0.3017	0.4592	$P_3 \succ P_1 \succ P_2$
0.2	0.4248	-0.3037	0.4613	$P_3 \succ P_1 \succ P_2$
0.3	0.4220	-0.3057	0.4636	$P_3 \succ P_1 \succ P_2$
0.4	0.4157	-0.3061	0.4665	$P_3 \succ P_1 \succ P_2$
0.5 (Integrated weight)	0.4088	-0.3067	0.4697	$P_3 \succ P_1 \succ P_2$
0.6	0.4011	-0.3075	0.4734	$P_3 \succ P_1 \succ P_2$
0.7	0.3926	-0.3086	0.4775	$P_3 \succ P_1 \succ P_2$
0.8	0.3828	-0.3102	0.4823	$P_3 \succ P_1 \succ P_2$
0.9	0.3714	-0.3123	0.4877	$P_3 \succ P_1 \succ P_2$
1.0 (Objective by MEREC)	0.3580	-0.3152	0.4939	$P_3 \succ P_1 \succ P_2$

5.2.Comparative Analysis

The current section presents the comparative study between proposed and previously developed MCDM models. For this purpose, we have chosen some previous methods such as "interval-valued Fermatean fuzzy technique for order of preference by similarity to ideal solution (IVFF-TOPSIS) (Jeevaraj, 2021)", "interval-valued Fermatean fuzzy weighted sum model (IVFF-WSM) (Sergi et al., 2021)" and "interval-valued Fermatean fuzzy weighted aggregated sum product assessment (IVFF-WASPAS) (Rani and Mishra, 2022)" and implemented on the discussed case study of climate change-resilient transportation alternatives evaluation.

5.2.1. IVFF-TOPSIS method

Commented [ZY9]: Again, I would suggest to this to the appendix. This whole section is entitled 'Results' and I don't think method should be discussed here. I would move and merge this section with previous section, and as previously suggested to put in an appendix/supplement. It is also number as steps so it is only logical to go together with the previous section. Only the result, in this section.

This method involves the following stages

Steps 1-4: Same as the proposed method

Step 5: The "IVFF-positive ideal solution (IVFF-PIS)" and "IVFF-negative ideal solution (IVFF-NIS)" are computed by

$$\wp^{+} = \begin{cases} \left[\max\limits_i \mu_{ij}^{lb}, \max\limits_i \mu_{ij}^{ub} \right], & \text{for benefit criterion } j \in Q_b \\ \left[\min\limits_i \nu_{ij}^{lb}, \min\limits_i \nu_{ij}^{ub} \right], & \text{for cost criterion } j \in Q_n \end{cases}, \tag{23}$$

$$\wp^{-} = \begin{cases} \left[\min\limits_i \mu_{ij}^{lb}, \min\limits_i \mu_{ij}^{ub} \right], & \text{for benefit criterion } j \in Q_b \\ \left[\max\limits_i \nu_{ij}^{lb}, \max\limits_i \nu_{ij}^{ub} \right], & \text{for cost criterion } j \in Q_n \end{cases}, \tag{24}$$

where $\wp^{+}$ and $\wp^{-}$ denote the IVFF-PIS and IVFF-NIS, respectively.

Step 6: Find the distance measure from IVFF-PIS and IVFF-NIS, respectively, given as

$$d\left(P_i, \wp^{+}\right) = \sum_{j=1}^{t} w_j \sqrt{\frac{1}{6}\left[\begin{array}{l} \left(\left(\mu_{ij}^{lb}\right)^3 - \left(\mu_{\eta_j^+}^{lb}\right)^3\right)^2 + \left(\left(\mu_{ij}^{ub}\right)^3 - \left(\mu_{\eta_j^+}^{ub}\right)^3\right)^2 + \left(\left(\nu_{ij}^{lb}\right)^3 - \left(\nu_{\eta_j^+}^{lb}\right)^3\right)^2 \\ + \left(\left(\nu_{ij}^{ub}\right)^3 - \left(\nu_{\eta_j^+}^{ub}\right)^3\right)^2 + \left(\left(\pi_{ij}^{lb}\right)^3 - \left(\pi_{\eta_j^+}^{lb}\right)^3\right)^2 + \left(\left(\pi_{ij}^{ub}\right)^3 - \left(\pi_{\eta_j^+}^{ub}\right)^3\right)^2 \end{array} \right]} \tag{25}$$

$$d\left(P_i, \wp^{-}\right) = \sum_{j=1}^{t} w_j \sqrt{\frac{1}{6}\left[\begin{array}{l} \left(\left(\mu_{ij}^{lb}\right)^3 - \left(\mu_{\eta_j^-}^{lb}\right)^3\right)^2 + \left(\left(\mu_{ij}^{ub}\right)^3 - \left(\mu_{\eta_j^-}^{ub}\right)^3\right)^2 + \left(\left(\nu_{ij}^{lb}\right)^3 - \left(\nu_{\eta_j^-}^{lb}\right)^3\right)^2 \\ + \left(\left(\nu_{ij}^{ub}\right)^3 - \left(\nu_{\eta_j^-}^{ub}\right)^3\right)^2 + \left(\left(\pi_{ij}^{lb}\right)^3 - \left(\pi_{\eta_j^-}^{lb}\right)^3\right)^2 + \left(\left(\pi_{ij}^{ub}\right)^3 - \left(\pi_{\eta_j^-}^{ub}\right)^3\right)^2 \end{array} \right]}. \tag{26}$$

Here, $d\left(P_i, \wp^{+}\right)$ denotes the distance measure between P_i and IVFF-PIS, and $d\left(P_i, \wp^{-}\right)$ denotes the distance measure between P_i and IVFF-NIS, where i=1,2,…,s.

Step 7: Compute the closeness coefficient $\left(C\left(P_i\right)\right)$ of each alternative using Eq. (27),

$$C\left(P_i\right) = \frac{d\left(P_i, \wp^{-}\right)}{d\left(P_i, \wp^{+}\right) + d\left(P_i, \wp^{-}\right)}, \quad i = 1, 2, ..., s. \tag{27}$$

Step 8: Prioritize the alternatives in accordance with the values of the closeness coefficient.

The IVFF-PIS and IVFF-NIS are computed by Eqs (23)-(24), given as

$\wp^{+}$ = {([0.206, 0.278], [0.834, 0.901]), ([0.141, 0.220], [0.859, 0.910]), ([0.279, 0.358], [0.777, 0.846]), ([0.228, 0.313], [0.794, 0.865]), ([0.131, 0.216], [0.854, 0.905]), ([0.114, 0.200], [0.859, 0.910]), ([0.517, 0.621], [0.610, 0.728]), ([0.876, 0.938], [0.076, 0.146]), ([0.752, 0.851], [0.200, 0.308]), ([0.289, 0.379], [0.809, 0.875]), ([0.619, 0.736], [0.424, 0.564]), ([0.855, 0.928], [0.104, 0.195])},

$\wp^{-}$ = {([0.470, 0.567], [0.698, 0.798]), ([0.393, 0.469], [0.738, 0.835]), ([0.152, 0.240], [0.841, 0.892]), ([0.550, 0.654], [0.521, 0.578]), ([0.415, 0.520], [0.676, 0.761]), ([0.428, 0.536], [0.709, 0.802]), ([0.552, 0.624], [0.488, 0.613]), ([0.553, 0.684], [0.512, 0.622]), ([0.621, 0.738], [0.427, 0.502]), ([0.607, 0.707], [0.415, 0.532]), ([0.342, 0.443], [0.689, 0.778]), ([0.591, 0.710], [0.470, 0.609])}.

Table 2
Outcomes of IVFF-TOPSIS for an alternative selection.

Options	$d\left(P_i,\wp^{+}\right)$	$d\left(P_i,\wp^{-}\right)$	$C(P_i)$	Ranking
P_1	0.028	0.042	0.5976	2
P_2	0.050	0.016	0.2400	3
P_3	0.019	0.032	0.6260	1

From Eqs (25)-(27), we implement the IVFF-TOPSIS model and the outcomes are depicted in Table 2. Based on Table 2, the ranking prioritization order of the alternatives is $P_3 \succ P_1 \succ P_2$. Thus, the optimal option is P_3.

Commented [ZY10]: This needs to change if you move equations to the appendix.

5.2.2. IVFF-WASPAS method

Commented [ZY11]: Ibid. Method discussion should not be featured in the section entitled 'Results', following my previous suggestions.

Steps 1-4: Same as the proposed method

Step 5: Calculate the measures of the "weighted sum model (WSM)" $\square_i^{(1)}$ and "weighted product model (WPM)" $\square_i^{(2)}$ for i^{th} alternative, given as

$$\square_i^{(1)} = \bigoplus_{j=1}^{t} w_j\, \varepsilon_{ij}. \tag{28}$$

$$\square_i^{(2)} = \bigotimes_{j=1}^{t} \varepsilon_{ij}^{w_j}. \tag{29}$$

Step 7: Determine the WASPAS measure degree for each alternative, given as

$$\square_i = \lambda \square_i^{(1)} + (1-\lambda) \square_i^{(2)}, \tag{30}$$

where ‘ $\lambda \in [0,1]$ ’ denotes the strategy coefficient.

Step 8: Estimate the preference order of the alternatives using WASPAS measure.

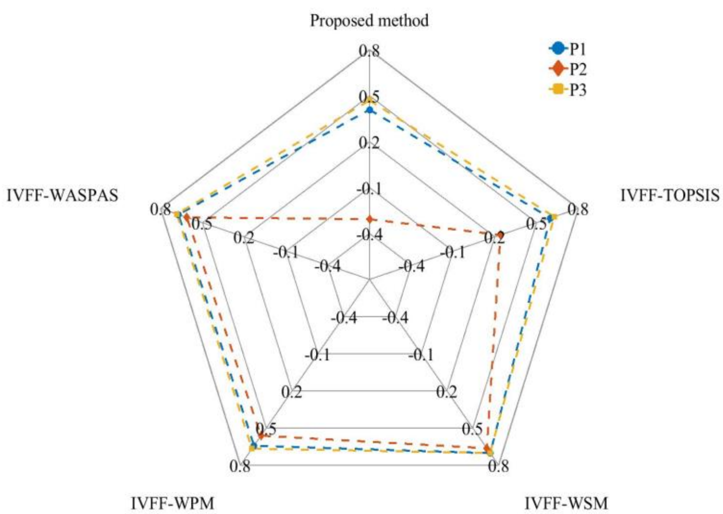
The overall results of the IVFF-WASPAS method are presented in Table 3 (for λ = 0.5).

Table 3

Computational outcomes of IVFF-WASPAS model.

Options	WSM		WPM		$\square_i$	Ranking
	$\square_i^{(1)}$	$S(\square_i^{(1)})$	$\square_i^{(2)}$	$S(\square_i^{(2)})$		
P_1	([0.725, 0.813], [0.315,0.423])	0.7029	([0.681, 0.771], [0.417,0.511])	0.6420	0.6724	2
P_2	([0.693, 0.779], [0.367,0.470])	0.6632	([0.601, 0.706], [0.492,0.588])	0.5614	0.6123	3
P_3	([0.724, 0.820], [0.336,0.445])	0.7013	([0.696, 0.797], [0.392,0.490])	0.6663	0.6838	1

The preference ordering of the options is $P_3 \succ P_1 \succ P_2$. Thus, the optimal option is P_3.



~~**Fig. 4.**~~ **Fig. 3** Deviation of utility/closeness index of each option with the extant models

From ~~Tables 10-13~~ Table 1-3, we scrutinize that the optimal option is P_3. Furthermore, the ranking order of the three options computed by the proposed approach is identical to those evaluated by the IVFF-TOPSIS, IVFF-WSM, and IVFF-WASPAS methods. In addition, ~~Fig. 4~~ Fig. 3 presents the final assessment degrees of the options.

Based on a comparative study, we highlight the merits of the IVFF-MEREC-RS-MULTIMOORA approach, presented as follows:

- The proposed method considers both types (i.e., benefit and cost) of the criteria. Considering the benefit and cost types of criteria with multifaceted proportions offers more precise information. Consequently, it enhances not only the readability of initial information but also the precision of the results.
- Existing IVFF-information-based decision-making methods given by (Jeevaraj, 2021; Sergi et al., 2021) consider the direct weights of criteria, and the methods (Rani and Mishra, 2022; Rani et al., 2022) compute the objective weights of criteria. While, the proposed MCDM methodology combines the objective and subjective criteria weight-determining models, which makes the present method more practical, accurate, and flexible.
- In comparison with IVFF-TOPSIS, IVFF-WSM, and IVFF-WASPAS, the developed MULTIMOORA method gives more accurate results because it integrates three models and employs their relevant benefits to finally obtain a more robust result than the individual result.
- Based on the comparison with IVFF-TOPSIS, IVFF-WSM, and IVFF-WASPAS, we obtain that the results of IVFFHWAO and IVFFHWGO could be more reasonable as they are generalized versions of algebraic sum and product operators.
- The developed MULTIMOORA method offers a more accurate ranking result by integrating the advantages of IVFF-MEREC and IVFF-RS in estimating the weights of the criteria. As a result, the presented method is more valuable in finding the reasonable weights of evaluation criteria and deciding the precise significance of the DEs in the evaluation of climate change-resilient transportation alternatives.

6. Policy Implication

The creation of sustainable, resilient transportation networks against climate change has become a necessity in the 21st century. There is an urgent need to make transportation systems resilient against climate change and make them prepared for changing conditions. Hence, this study showed that experts focus on more rational and long-term solutions instead of short-term solutions. The findings of this study should be taken into consideration by authorities and decision-makers who are working toward the transition to a transportation system that is more resilient to the effects of climate change. These individuals should work toward a long-term policy rather than a short-term policy.

Traffic demand, environmental factors, and financial conditions were the points to be considered while evaluating the criteria. However, instead of choosing the easiest and cheapest alternative, the third alternative is the most logical alternative that can relieve both financial and traffic demands. In addition, the applicability of the alternatives in this research is suitable in cities with large and complex transportation networks. Furthermore, the sustainability and feasibility of this study can be considered more in cities where climate change is severely affected; therefore, it is beneficial. On the other hand, the alternative that was decided to be the most advantageous one is a novel application, which has not been investigated extensively in the published literature and is not one that is commonly utilized in the reality. Consequently, developing policies in terms of the implementations of the alternative is of great benefit to the authorities since it provides them with the potential to serve as a guide.

Commented [ZY12]: I would generally move this section down and make it follows the discussion section.

7. Discussion

Considering this study, three different alternatives are evaluated based on twelve different criteria that are listed under four major criteria sides. To manage the evaluation, a questionnaire is formed inside of which alternatives are requested to be assessed following each criterion. Afterward, the questionnaire is sent to experts in the field and each alternative is evaluated based on the criteria. Using the proposed MCDM method technique, P_3 (Preparing operationally to the effects of climate change) was the most advantageous alternative, while P_1 (Climate change the resistant design of transportation facilities) was the most advantageous alternative after P_3. Finally, P_2 (Providing alternative routes and strategies for the transportation system) was the least advantageous alternative.

The most advantageous alternative is preparing operationally for the effects of climate change. Intervening operationally for disruptions in transportation infrastructure due to climate change is the most significant alternative to creating an efficient and feasible transportation network. For example, transportation activities may be disrupted under heavy weather, especially in heavy rain conditions, and many people may be adversely affected by this situation. By preparing the transportation activities operationally, the transportation network can be sustained with minimum damage.

Climate change in the resistant design of transportation facilities is the second most advantageous alternative. Since heavy snowfalls, rains, storms or floods can happen due to climate change, transportation facilities may become unusable due to these natural reasons. Considering the transportation infrastructure and climate change, it is possible to use durable, resilient transportation networks most effectively and beneficially.

Providing users with alternative routes and strategies so that transportation systems are least affected by climate change can solve the problem; however, this can increase traffic density even more. While this alternative can be useful in some road networks, the possibility of increasing the traffic problems in cities with heavy traffic networks has made this alternative the least desirable alternative.

8. Conclusions

Climate change is becoming a significant problem day by day. Natural disasters (floods, snow slides, storms, etc.) that occur every year leave more impact. These effects sometimes cause temporary and sometimes permanent consequences. Unfortunately, today's transportation facilities can be helpless in the face of these increasing problems. For this reason, the creation of resilient transportation networks, both in design, operational and strategic terms, will help create a sustainable, feasible, and effective transportation network. This paper will contribute to the studies on the impact of climate change on resilience transportation networks, which are not sufficient in the literature. Through this paper, resilient transportation networks will offer clearer and more rigid solutions to modern problems. The strategy utilized in this study to achieve these goals is to provide three different climate change-resilient transportation alternatives, two of which are novel and one of which is thoroughly investigated, and to prioritize these alternatives based on their advantages as determined by expert reviews. According to the findings, the most beneficial approach is to make operational preparations for the consequences that climate change will have, and the second most beneficial alternative is to construct transportation infrastructure so that they are resistant to the effects of climate change. In conclusion, it has been determined that giving alternate ways to travel and different strategies for the transportation system is the option that offers the fewest benefits.

In this study, we have proposed an IVFFI-based MULTIMOORA method based on the Hamacher AOs and a novel weighting procedure. Here, the objective weights of criteria have been derived by the MEREC model and the subjective weights of criteria have been determined based on the RS method under the IVFF environment. Then, a combined weighting model is presented to obtain the final weights of the criteria. Further, a case study of the climate change-resilient transportation alternatives assessment problem has been implemented from interval-valued Fermatean fuzzy perspectives, which expresses the usefulness and practicability of the introduced methodology. Sensitivity analysis and comparative study have been presented to check the robustness and stability of the proposed method.

Further, a comparison with existing methods has been discussed to explain the strength and reliability of the proposed MULTIMOORA method. As per the comparative study, it can be observed that the proposed method is very useful and appropriate for MCDM problems with uncertain and incomplete information. However, the proposed MCDM method still has some limitations:

- This method ignores the interrelationships among the criteria.
- The proposed method has limitations in using a onefold normalization procedure, which would bias the outcomes because of the fault normalized values for aggregation.

In the future, we will try to overcome the limitations of the present MCDM method in further studies. Moreover, we will extend the proposed MULTIMOORA method to the Fermatean hesitant fuzzy sets, interval-valued Fermatean hesitant fuzzy sets, and bipolar fuzzy sets environments.

In addition to the limitations imposed by the novel MCDM method, there are also limits placed when the case study is taken into consideration. For instance, out of the three different options presented in this study, two of them are brand new applications that have not been properly investigated in the relevant literature. Because of this, the potential advantages and disadvantages of utilizing these alternate options are not yet fully understood. The number of possible alternatives can be expanded upon when prospective research topics about the subject of this study are taken into consideration. In addition, the criteria that were utilized in this research might be expanded to perform a more comprehensive analysis of the available options. On the other hand, a pilot project area may be chosen, and the options that are deemed to be advantageous can be implemented in the area so that the effects that are brought about by these applications can be observed. This allows for a more informed decision-making process.

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