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Sustainable Public Transportation System Evaluation: A Novel Two-Stage Hybrid Method Based on IVIF-AHP and CODAS

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Abstract As a multi-disciplinary process, planning of public transportation systems needs special attention from several groups of stakeholders such as passengers, transportation planners, system providers, and so on. Since each stakeholder has dissimilar viewpoints on the evaluation of the public transportation systems, they have contradictory goal and objectives. In this sense, multi-criteria decision-making (MCDM) provides an important procedural outline for the evaluation of public transportation alternatives. This paper presents an application of MCDM method to assess the public transportation alternatives designed for a public university in a large-sized metropolitan area. Two alternatives of MCDM methods, named Interval-Valued Intuitionistic Fuzzy Analytical Hierarchy Process & COmbinative Distance-based Assessment (IVIF-AHP & CODAS), are integrated in the evaluation process. The proposed method ensures consistent and reasonable results and provides suggestions for the forthcoming progresses of public transportation service quality. In order to validate robustness of the proposed method, sensitivity analyses are implemented. Also, at the end of the study, to prove the superiority of the proposed approach, a comparative analysis is employed.

Keywords MCDM · IVIF · AHP · CODAS · Public transportation

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1 Introduction

The transportation plays a vital role in everyday life of people and influences public in many aspects including economic, environmental, cultural, and so on. Public transport or mass transit systems provide mobility to public and these systems consist of trains, cars, buses, ferryboats, bicycles, pedestrian paths, trucks, etc. Furthermore, planning in public transportation relates to providing mobility and ease of access for everyone that uses such systems [1].

Additionally, transportation planning is one of the most important essentials to develop sustainable metropolitan environment. Accessible and safe transport systems lead to more efficient and environmentally sustainable urban development [2]. Therefore, transportation planners need to design transportation systems for the entire county. During the planning stage, planners work with the public, municipalities, and other agencies considering different aspects and sophisticated computer systems to forecast future travel needs and realize projects that are appropriate to their region considering limited funds [1]. The establishment of such association may increase the value of public transportation services, and the performance of these services can be evaluated considering efficiency, effectiveness, economics, social, environmental, speed, frequency of cars, line configuration, and capacity [2].

Since the public transportation planning process is deliberated as a strategic decision for public and private sectors, numerous MCDM methodologies have been suggested by researchers. The objective of this study is to determine the most appropriate public transportation alternative to provide a sustainable transportation within a university campus using a novel decision-making approach, which combines Analytical Hierarchy Process (AHP) and CODAS methods under Interval-Valued

Intuitionistic Fuzzy (IVIF) environment. The aims of the study consists the following issues:

- improve vehicular connection between the buildings of the university within the campus area in a metropolitan city of Turkey,
- suggest safer and faster transportation system for passengers, who mostly are faculty, staff, and students, and
- provide a long-term plan and sustainability for transportation mode of traveling.

It is evident from the previous studies that an integrated IVIF-AHP & CODAS approach is the first presented methodology to select the most appropriate public transportation system, because the proposed method ensures consistent and reasonable results and provides suggestions for forthcoming developments of public transportation service quality.

Since the complexity of the problem, studied in this study, requires development of a hierarchical structure a pairwise comparison of the criteria is used due to the fact that the weights of the criteria are not available in advance, and AHP is one of the best alternative to determine criteria weights by using pairwise comparisons. Another advantage of the AHP is to be able to calculate the consistency of the obtained results. On the other hand, IVIF is used because it is hard for decision-makers (DMs) to evaluate criteria and alternatives in a linguistic format considering only membership functions as in classical fuzzy set theory. Oppositely, IVIF set has more powerful type fuzzy numbers to cope with fuzzy and uncertain environment by allowing DMs to use both membership and non-membership function within closed interval numbers in the decision-making process. Hence, the IVIF version of AHP, which has the advantage of allowing a hierarchical configuration of the main and sub-criteria, is used to calculate the weights of both main and sub-criteria [3, 4].

In addition, IVIF-CODAS has the advantage of providing more reliable ranking outcomes using the advantage of both Euclidian and Hamming distances. Furthermore, IVIF-CODAS provides less computational time and transparent computation process comparing with other MCDM methods [5]. CODAS is presented as a MCDM method firstly by Ghorabaee et al. [6].

In this study, once the criteria and sub-criteria weights are determined using IVIF-AHP, which is proposed by Wu et al. [7], CODAS is integrated for determining the rank of public transportation alternatives based on their overall performances. As a result, this study provides a tool to analyze decision-making criteria esteemed by public (students, academicians, and servants) to choose a public transit system for transportation within a university campus. Accordingly, this study helps to determine the importance of criteria and their effects on public behavior toward public transportation services.

The remaining of the study is constructed as follows: in Sect. 2, a brief of literature on MCDM in public transportation and IVIF-AHP and CODAS are presented. In Sect. 3, the required preliminaries of the proposed approach are explained, while in Sect. 4, the proposed approach is presented. The case of selecting public transportation system for a university campus is applied to represent applicability and feasibility of the proposed approach in Sect. 5. Then, comparative and sensitivity analyses of the proposed approach are provided to validate the results. Lastly, in Sect. 6, conclusions and future directions are presented.

2 Literature Review on MCDM and IVIF-AHP & CODAS

MCDM method is an extensively used technique in decision-making problems both in public transportation and other fields [8, 9]. MCDM refers to decision-making processes considering multiple, usually conflicting, criteria and decision alternatives. In other words, models developed in MCDM are constructed to assess a finite set of alternatives regarding several criteria [2].

MCDM methods have been effectively implemented to public transportation system selection problem in literature, such that several types of MCDM methods have been used by transportation system designers and they have become a more preferable and powerful technique than cost–benefit analyses. Mostly, the aim of such MCDM approaches is to determine the best transportation alternative that meets several criteria and an extensive variety of goals [10]. For instance, Jakimavicius and Burinskiene and Jeon et al. [11, 12] suggested multi-criteria analysis, called a graphical–analytical method, to complete a modified four-step transport planning study. Nijkamp et al. [13] proposed a multi-criteria assessment framework including land use and transport modeling. Keumi and Murakami [14] evaluated the transportation alternatives and proposed multiple transportation service levels that ease accessing to an international airport. Zak [15] presented an application of MCDM and MCDM aiding (MCDMA) methodology to assess the mass transit system projects for a public transportation company.

However, considering to satisfy public transportation passengers, MCDM become one of the promising tool which has been preferred by several DMs and managers [16, 17]. Researchers established the most common criteria as passenger's time savings, safety, cost, comfort, traffic volume, travel distance, and security [18–22]. Eboli and Mazulla [23] presented a framework with respect to air passengers' satisfaction and claimed that comfort and cleanliness are very important issues for passengers. Aydin, and Zheng and Jiaqing [8, 24] pointed that passengers desire the best service quality and fast responsiveness that is provided by private or public firms.

Subjectivity (fuzziness, ambiguity) of the evaluators is another issue in MCDM techniques. To handle this concern, several researchers have proposed fuzzy set theory (FST) while assessing transportation projects. For instance, Teng and Tzeng [25] presented the use of a 0–1 fuzzy multi-objective programming model for the evaluation of transportation investments. Soltani et al. [26] proposed an integrated model of Fuzzy AHP and TOPSIS to define the existing conditions of public transportation considering the bus routes to develop the services, merge existing routes, and create new routes. Arslan [27] proposed a fuzzy AHP method to choose appropriate public bus transportation systems for municipal establishments and private organizations. Hanaoka and Kunadhamraks [28] applied fuzzy AHP to assess the performance measures in intermodal freight transportation. Celik et al. and Hassan et al. [29, 30] stated that the existing and forecasted demand trends, hesitations of stakeholders, and unsatisfied service necessities must be considered in the evaluation framework. Kundu [31] proposed a fuzzy MCDM technique to determine the most appropriate transportation type considering several criteria for a solid transportation problem (STP). Zak [32] presented a hybrid technique and combined the concepts and procedures of MCDM/A methods (ELECTRE, AHP) for a transportation oriented decision-making problem. Several researchers have obtained transportation problem employing intuitionistic or interval-valued intuitionistic fuzzy system [33–37]. For sustainability in transportation, Mihyeon and Amekudzi [38] reviewed the foremost initiatives in North America, Europe, and Oceania to describe what establishes sustainable transportation. They determined that the influences of the structure on the economy, social well-being, and environmental issues are important in assessing sustainability of the transportation. Later, Awasthi et al. [39] pointed out the importance of the sustainable transportation and proposed a framework for DMs to take decisions under uncertain environment. After determining assessment criteria, they used fuzzy TOPSIS to assess the alternatives and then provided sensitivity analysis to show the applicability of the proposed framework. Furthermore, Shiau [40] developed a hybrid framework to evaluate and rank sustainable transportation strategies for Taipei City. Considering 15 alternate strategies, they created a multifactorial guide, which includes characteristics of society, finance, environmental issues, economy, and energy, to evaluate sustainability of transportation.

To overcome uncertainty and ambiguity mostly in the process of decision-making, different fuzzy extensions are preferred by researchers. One of the suggested and used fuzzy number within the literature is IVIF number. Therefore, in the decision-making course, CODAS is applied using IVIF numbers as in Bolturk and Kahraman [41]. Bolturk and Kahraman [41] introduced IVIF-CODAS, the first time, which considers both Euclidean and Taxicab distances with regard to negative ideal point. The effectiveness of the proposed method is shown by an application in a wave energy facility location selection problem. IVIF-based CODAS method becomes more preferable by researchers lately. Three of the latest publications are done by Roy et al. [5], Yeni and Ozcelik [42], and Seker [43]. Roy et al. [5] suggested CODAS method with IVIF numbers considering incomplete weight information. Yeni and Ozcelik [42] applied Interval-Valued Atanassov Intuitionistic Fuzzy CODAS (IVAIF-CODAS) in a personnel selection problem. On the other hand, Seker [43] integrated CODAS-based Interval-Valued Intuitionistic Trapezoidal Fuzzy Set (IVITrFS) to take decisions in selection of investment projects. Latest applications of IVIF-based CODAS encouraged authors to develop an integrated method based on IVIF-AHP and CODAS to get more accurate, effective, and efficient results in MCDM problems under uncertain environment.

In this study, IVIF set is applied to handle uncertain and vague information of the DMs' subjective preferences using membership degree, non-membership degree, and hesitation. The objective of this study is to determine the most convenient transportation system to transfer students, academicians, visitors, and university personnel along the campus in a metropolitan city of Turkey. Selection of the best transportation system, which refers to socioeconomic environment, involves complex and sophisticated decision variables. As a solution tool, a multi-disciplinary procedure, which necessitates the consideration of a set of criteria and the needs of stakeholders, is developed and two alternative MCDM methods named AHP and CODAS have been integrated under IVIF environment for the first time in the literature.

3 Preliminaries

Some basic and required notions with respect to IVIF numbers will be introduced in this section.

Definition 1 Atanassov [44] developed the concept of intuitionistic fuzzy sets to handle more flexible and imprecise information than the ordinary FST. Let Q be nonempty set, $A = \{ <x, \mu_A(x), \nu_A(x) > x \in Q\}$ is a initionistic fuzzy set where $\tilde{\mu}_A(x)$ is the membership degree of

x belongs to Q, $\tilde{v}_A(x)$ is the non-membership degree of x belongs to Q, $\mu_A : x \to [0,1], v_A : x \to [0,1]$, and $0 \leq \tilde{\mu}_A(x) + \tilde{v}_A(x) \leq 1$. $\forall x \in X$. Moreover, $1 - \tilde{\mu}_A(x) - \tilde{v}_A(x)$ refers to the hesitancy degree of x belongs to A.

Definition 2 The arithmetic operations over IVIF numbers can be expressed as follows [45]. Let $\tilde{\alpha}_1 = \left[\mu^-_{\tilde{\alpha}_1}, \mu^+_{\tilde{\alpha}_1}\right]; \left[v^-_{\tilde{\alpha}_1}, v^+_{\tilde{\alpha}_1}\right]$ and $\tilde{\alpha}_2 = \left[\mu^-_{\tilde{\alpha}_2}, \mu^+_{\tilde{\alpha}_2}\right]; \left[v^-_{\tilde{\alpha}_2}, v^+_{\tilde{\alpha}_2}\right]$ be two IVIF numbers and $\lambda \geq 0$, then

$$\tilde{\alpha}_1 \oplus \tilde{\alpha}_2 = \left[\mu^-_{\tilde{\alpha}_1} + \mu^-_{\tilde{\alpha}_2} - \mu^-_{\tilde{\alpha}_1}\mu^-_{\tilde{\alpha}_2}, \mu^+_{\tilde{\alpha}_1} + \mu^+_{\tilde{\alpha}_2} - \mu^+_{\tilde{\alpha}_1}\mu^+_{\tilde{\alpha}_2}\right], \left[v^-_{\tilde{\alpha}_1} v^-_{\tilde{\alpha}_2}, v^+_{\tilde{\alpha}_1} v^+_{\tilde{\alpha}_1}\right] \quad (1)$$

$$\tilde{\alpha}_1 \otimes \tilde{\alpha}_2 = \left[\mu^-_{\tilde{\alpha}_1}\mu^-_{\tilde{\alpha}_2}, \mu^+_{\tilde{\alpha}_1}\mu^+_{\tilde{\alpha}_2}\right], \left[v^-_{\tilde{\alpha}_1} + v^-_{\tilde{\alpha}_2} - v^-_{\tilde{\alpha}_1}v^-_{\tilde{\alpha}_2}, v^+_{\tilde{\alpha}_1} + v^+_{\tilde{\alpha}_2} - v^+_{\tilde{\alpha}_1}v^+_{\tilde{\alpha}_2}\right]\Big) \quad (2)$$

$$\lambda\tilde{a} = \left[1 - \left(1 - \mu^-_{\tilde{\alpha}}\right)^{\lambda}, 1 - \left(1 - \mu^+_{\tilde{\alpha}}\right)^{\lambda}\right], \left[\left(v^-_{\tilde{\alpha}}\right)^{\lambda}, \left(v^+_{\tilde{\alpha}}\right)^{\lambda}\right] \quad (3)$$

$$\tilde{a}^{\lambda} = \left[\left(\mu^-_{\tilde{\alpha}}\right)^{\lambda}, \left(\mu^+_{\tilde{\alpha}}\right)^{\lambda}\right], \left[\left[1 - \left(1 - \left(v^-_{\tilde{\alpha}}\right)\right)^{\lambda}, \left(1 - \left(1 - v^+_{\tilde{\alpha}}\right)\right)^{\lambda}\right]. \quad (4)$$

Definition 3 Let $\alpha = \left[\tilde{\mu}^-_{ij}, \tilde{\mu}^+_{ij}\right], \left[\tilde{v}^-_{ij}, \tilde{v}^+_{ij}\right]$ is an IVIF number. Defuzzification formula is used as:

$$\mathfrak{D}(\alpha) = \frac{\tilde{\mu}^-_{ij} + \tilde{\mu}^+_{ij} + \left(1 - \tilde{v}^-_{ij}\right) + \left(1 - \tilde{v}^+_{ij}\right) + \tilde{\mu}^-_{ij}\tilde{\mu}^+_{ij} - \sqrt{\left(1 - \tilde{v}^-_{ij}\right)\left(1 - \tilde{v}^+_{ij}\right)}}{4} \quad (5)$$

Some aggregation operators with respect to IVIF numbers are developed, and one of these operators is used in this paper. This aggregation operator is as follows:

Definition 4 IVIF Hybrid Geometric (IVIFHG) operator: Let $\tilde{\alpha}^k_{ij} = \left[\mu^-_{\tilde{\alpha}}, \mu^+_{\tilde{\alpha}}\right]; \left[v^-_{\tilde{\alpha}}, v^+_{\tilde{\alpha}}\right]$; be the IVIF numbers where $j = 1, 2,\ldots,n$. Utilizing from IVIFHG operator as in Eq. (6), the aggregated IVIF numbers $\tilde{\alpha}^A_{ij}$ is obtained [46]:

$$\text{IVIFHG}(\tilde{\alpha}_1, \tilde{\alpha}_2, \ldots, n) = \sum_{j=1}^{n} w_j\tilde{\alpha}_j = \left(\left[\prod_{j=1}^{n}\left(\mu^-_j\right)^{w_j}, \prod_{j=1}^{n}\left(\mu^+_j\right)^{w_j}\right], \left[1 - \prod_{j=1}^{n}\left(1 - v^-_j\right)^{w_j}, 1 - \prod_{j=1}^{n}\left(1 - v^+_j\right)^{j}\right]\right) \quad (6)$$

where w_k is the weight vector of expert k. $W = (w_1, w_2, \ldots, w_n)^T$ such that $w_j \geq 0$, then, if $w = \left(\frac{1}{n}, \frac{1}{n}, \ldots, \frac{1}{n}\right)$, $\sum_{j=1}^{n} w_j = 1$. $\sum_{j=1}^{n} w_j = 1$.

Definition 5 Let $\tilde{\alpha}_1 = \left[\mu^-_1, \mu^+_1\right]; \left[v^-_1, v^+_1\right]$ and $\tilde{\alpha}_2 = \left[\mu^-_2, \mu^+_2\right]; \left[v^-_2, v^+_2\right]$ be two IVIF numbers. The distance between these two IVIF numbers is calculated by Hamming distance (HD) as in Eq. (7) [47]:

$$HD = 1/4\sum\left(\left|\mu^-_1 - \mu^-_2\right| + \left|\mu^+_1 - \mu^+_2\right| + \left|v^-_1 - v^-_2\right| + \left|v^+_1 - v^+_2\right|\right. \quad (7)$$

Definition 6 Let $\tilde{\alpha}_1 = \left[\mu^-_1, \mu^+_1\right]; \left[v^-_1, v^+_1\right]$ and $\tilde{\alpha}_2 = \left[\mu^-_2, \mu^+_2\right]; \left[v^-_2, v^+_2\right]$ be two IVIF numbers. The distance between these two IVIF numbers is calculated by Euclidian distance (ED) as in Eq. (8):

$$\text{ED} = 1/2\sqrt{\sum\left(\mu^-_1 - \mu^-_2\right)^2 + \left(\mu^+_1 - \mu^+_2\right)^2 + \left(v^-_1 - v^-_2\right)^2 + \left(v^+_1 - v^+_2\right)^2} \quad (8)$$

Definition 7 For an IVIF number $\tilde{\alpha} = \left[\mu^-_{\tilde{\alpha}}, \mu^+_{\tilde{\alpha}}\right]; \left[v^-_{\tilde{\alpha}}, v^+_{\tilde{\alpha}}\right]$), the score function $S(\tilde{\alpha})$ and accuracy function $H(\tilde{\alpha})$ are defined as follows [48]:

$$S(\tilde{\alpha}) = 1/2\left(\mu^-_{\tilde{\alpha}} - v^-_{\tilde{\alpha}} + \mu^+_{\tilde{\alpha}} - v^+_{\tilde{\alpha}}\right) \quad S(\tilde{\alpha}) \in [-1, 1] \quad (9)$$

$$H(\tilde{\alpha}) = 1/2\left(\mu^-_{\tilde{\alpha}} + v^-_{\tilde{\alpha}} + \mu^+_{\tilde{\alpha}} + v^+_{\tilde{\alpha}}\right) \quad H(\tilde{\alpha}) \in [0, 1] \quad (10)$$

The degree of accuracy of the IVIF number $\tilde{\alpha}$ increases as the value of $H(\tilde{\alpha})$ increases. When two IVIF numbers are ranked, the score function S and the accuracy function H can be compared as follows:

Let $\tilde{\alpha}_1$ and $\tilde{\alpha}_2$ be two IVIF numbers.

If $S(\tilde{\alpha}_1) < S(\tilde{\alpha}_2)$, then $\tilde{\alpha}_1$ is smaller than $\tilde{\alpha}_2$, represented as $\tilde{\alpha}_1 < \tilde{\alpha}_2$.

If $S(\tilde{\alpha}_1) = S(\tilde{\alpha}_2)$, then If $H(\tilde{\alpha}_1) = H(\tilde{\alpha}_2)$, then $\tilde{\alpha}_1$ and $\tilde{\alpha}_2$ show the same evidence, represented as $\tilde{\alpha}_1 = \tilde{\alpha}_2$.

If $H(\tilde{\alpha}_1) < H(\tilde{\alpha}_2)$, then $\tilde{\alpha}_1$ is smaller than $\tilde{\alpha}_2$, represented as $\tilde{\alpha}_1 < \tilde{\alpha}_2$.

4 Proposed Approach: IVIF-AHP & CODAS

In this section, to assess the public transportation alternatives designed for a public university in a large-sized metropolitan area of Turkey, a novel integrated MCDM approach named IVIF-AHP & CODAS is proposed. The flow diagram of the proposed approach is summarized in Fig. 1. The stepwise application of the proposed approach is presented as follows:

Step 1: Obtain the weights of main and sub-criteria: After criteria and sub-criteria weights are obtained by

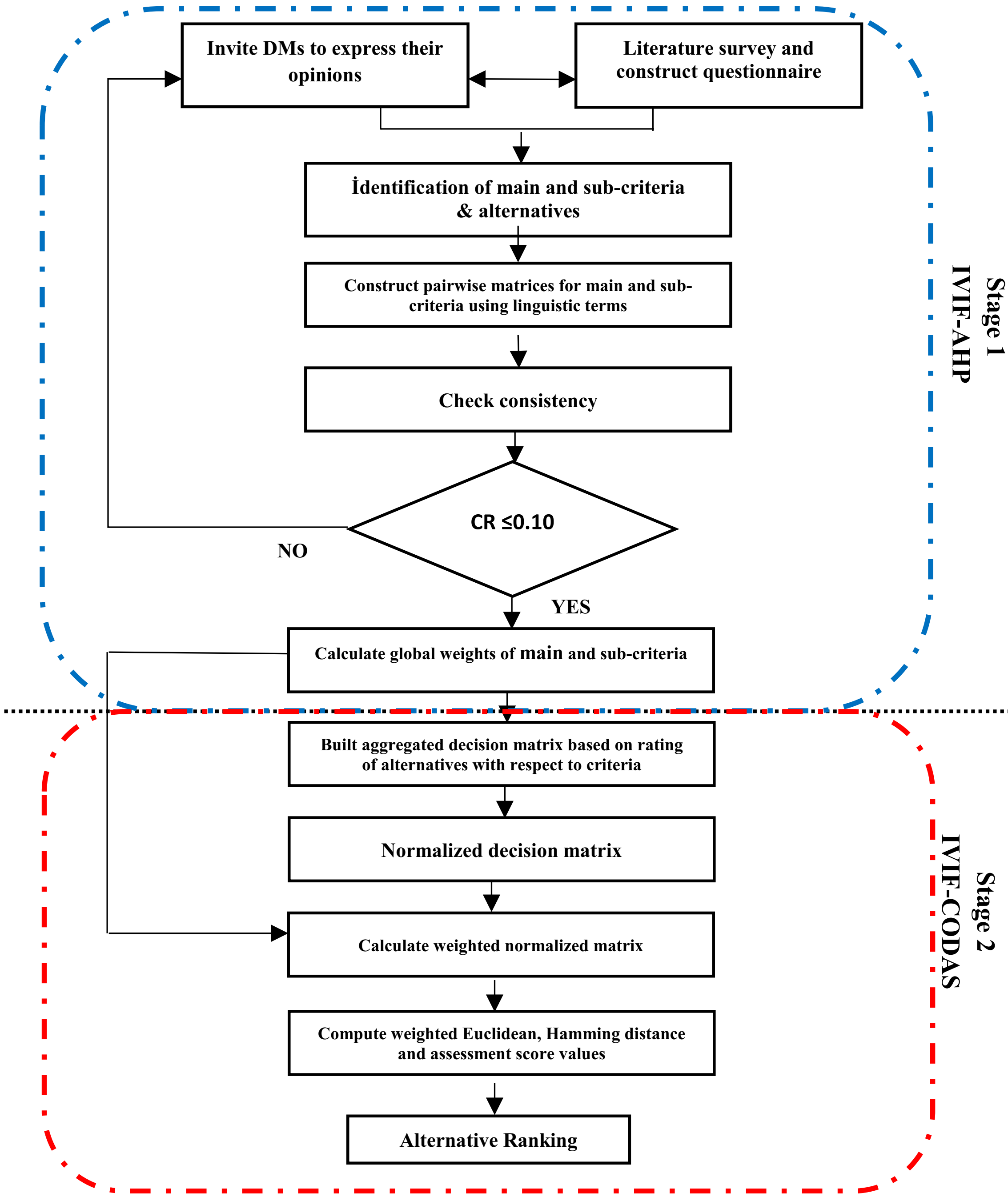

Fig. 1 The flow of the proposed integrated MCDM approach

IVIF-AHP proposed by Wu et al. [7], IVIF-CODAS method is used to rank transportation alternatives.

Step 2: Form the IVIF decision matrix ($\tilde{X}^k$) for each DM: Each DM, $k \in (1, 2\ldots q)$ evaluates the set of n alternatives $i \in (1, 2\ldots, n)$ based on m criteria $j \in (1, 2\ldots, m)$ using linguistic terms as given Tables 1, 2.

$$\tilde{X}^k = \begin{bmatrix} \tilde{x}^k_{11}\tilde{x}^k_{12} & \cdots & \tilde{x}^k_{1m} \\ \vdots & \ddots & \vdots \\ \tilde{x}^k_{n1}\tilde{x}^k_{n2} & \cdots & \tilde{x}^k_{nm} \end{bmatrix} \quad (11)$$

where $\tilde{x}^k_{ij}$ denotes the rating value of ith alternative related to jth criterion for each kth DM.

Table 1 Linguistic terms and corresponding IVIF numbers for weighting criteria

Linguistic term	IVIF number
Absolutely Low (AL)	⟨[0.10, 0.20],[0.70, 0.80]⟩
Very Low (VL)	⟨[0.15, 0.25],[0.65, 0.75]⟩
Low (*L*)	⟨[0.20, 0.30],[0.60, 0.70]⟩
Medium Low (ML)	⟨[0.25, 0.35],[0.55, 0.65]⟩
Exactly (EE)	⟨[0.50, 0.50],[0.50, 0.50]⟩
Medium High (MH)	⟨[0.55, 0.65],[0.25, 0.35]⟩
High (*H*)	⟨[0.60, 0.70],[0.20, 0.30]⟩
Very High (VH)	⟨[0.65, 0.75],[0.15, 0.25]⟩
Absolutely High (AH)	⟨[0.70, 0.80],[0.10, 0.20]⟩

Table 2 Linguistic terms and corresponding IVIF numbers to rate alternatives

Linguistic term	IVIF number
Extremely Bad (EB)	⟨[0.00, 0.10],[0.75, 0.90]⟩
Very Bad (VB)	⟨[0.05, 0.20],[0.65, 0.80]⟩
Bad (*B*)	⟨[0.15, 0.30],[0.55, 0.70]⟩
Medium Bad (MB)	⟨[0.25, 0.40],[0.45, 0.60]⟩
Medium (*M*)	⟨[0.50, 0.50],[0.50, 0.50]⟩
Medium Good (MG)	⟨[0.45, 0.60],[0.25, 0.40]⟩
Good (*G*)	⟨[0.55, 0.70],[0.15, 0.30]⟩
Very Good (VG)	⟨[0.65, 0.80],[0.05, 0.20]⟩
Extremely Good (EG)	⟨[0.75, 0.90],[0.00, 0.10]⟩

$$\tilde{x}_{ij}^{k} = \left\langle \left[\mu_{ij}^{k-}, \mu_{ij}^{k+}\right], \left[v_{ij}^{k-}, v_{ij}^{k+}\right] \right\rangle.$$

Step 3: Aggregate $\tilde{X}^{k} = \left(\tilde{x}_{ij}^{k}\right)_{m\times n}$ decision matrix: Evaluations of each DM are aggregated to obtain collective IVIF decision matrix $\tilde{X} = \left(\widetilde{x_{ij}^{A}}\right)_{m\times n}$ using Eq. (6) and then the aggregated IVIF decision matrix ($\tilde{X}$) is obtained.

Step 4: Normalize the aggregate IVIF decision matrix with respect to type of each criterion: In this step, evaluated values relating to cost criteria is converted to values relating to the benefit criteria. As an example, assume $\left(\tilde{x}_{ij}\right)^{c}$ is a cost criterion and shown as $\left(\tilde{x}_{ij}\right)^{c} = \left\langle \left[\mu_{ij}^{-}, \mu_{ij}^{+}\right], \left[v_{ij}^{-}, v_{ij}^{+}\right] \right\rangle$. It is transformed to benefit criteria as $\tilde{x}_{ij} = \left\langle \left[v_{ij}^{-}, v_{ij}^{+}\right], \left[\mu_{ij}^{-}, \mu_{ij}^{+}\right] \right\rangle$.

$\tilde{N} = \left[\tilde{n}_{ij}\right]_{n\times m}$

where n_{ij} shows the normalized IVIF rating values as in Eq. (12).

$$\tilde{n}_{ij} = \left[\mu_{ij}^{-} / \max_{i} \mu^{+}, \mu_{ij}^{+} / \max_{i} \mu^{+}\right], \left[v_{ij}^{-} / \max_{i} v^{+}, v_{ij}^{+} / \max_{i} v^{+}\right] \tag{12}$$

Step 5: Construct the weighted normalized IVIF decision matrix: The weights which are obtained by applying IVIF-AHP method are multiplied by normalized IVIF decision matrix. The weighted normalized IVIF decision matrix is obtained by using Eq. (13). $\tilde{S} = \left[\tilde{s}_{ij}\right]_{m\times n}$

$$\tilde{s}_{ij} = w_{i} \otimes \tilde{n}_{ij} \tag{13}$$

Step 6: Determine the negative ideal solution: The negative ideal solution is confirmed for a normalized IVIF decision matrix using following equations, respectively.

$$\widetilde{\mathrm{NS}} = \left[\widetilde{\mathrm{nsj}}^{-}\right]_{1\times m} \tag{14}$$

$$\widetilde{\mathrm{nsj}}^{-} = \min_{i} \left(\tilde{s}_{ij}\right) \tag{15}$$

$$\widetilde{\mathrm{nsj}}^{-} = \left\langle \left[\mu_{\tilde{\mathrm{ns}}}^{-}, \mu_{\tilde{\mathrm{ns}}}^{+}\right], \left[v_{\tilde{\mathrm{ns}}}^{-}, v_{\tilde{\mathrm{ns}}}^{+}\right] \right\rangle; \mathrm{ns} \in \mathrm{NS} \tag{16}$$

$$\tilde{n}_{sij}^{-} = \left[\min_{i} \mu_{ij}^{-}, \min_{i} \mu_{ij}^{+}\right], \left[\max_{i} v_{ij}^{-}, \max_{i} v_{ij}^{+}\right] \tag{17}$$

Step 7: Compute the IVIF weighted Euclidean Distance (ED) and IVIF weighted Hamming Distance (HD) for each alternative: To select the most suitable alternative, distance of each alternative from negative ideal solution is computed. The alternative which has greater distances from the negative ideal solution is more desirable. The distances are computed as follows:

$$\mathrm{ED}_{i} = \sum_{j=1}^{m} d_{E}\left(\tilde{s}_{ij}, \widetilde{\mathrm{nsj}}^{-}\right) \tag{18}$$

$$\mathrm{HD}_{i} = \sum_{j=1}^{m} d_{H}\left(\tilde{s}_{ij}, \widetilde{\mathrm{nsj}}^{-}\right) \tag{19}$$

$$ED_{i} = \frac{1}{2}\sqrt{\sum_{i=1}^{n}\left(\mu_{\tilde{s}}^{-} - \mu_{\widetilde{\mathrm{ns}}}^{-}\right)^{2} + \left(\mu_{\widetilde{\mathrm{ns}}}^{\pm} - \mu_{\widetilde{\mathrm{ns}}}^{\pm}\right)^{2} + \left(v_{\widetilde{\mathrm{ns}}}^{-} - v_{\widetilde{\mathrm{ns}}}^{-}\right)^{2} + \left(v_{\tilde{s}}^{+} - v_{\widetilde{\mathrm{ns}}}^{\pm}\right)^{2}} \tag{20}$$

$$\mathrm{HD}_{i} = \frac{1}{4}\sum \left|\mu_{\tilde{s}}^{-} - \mu_{\widetilde{\mathrm{ns}}}^{-}\right| + \left|\mu_{\tilde{s}}^{+} - \mu_{\widetilde{\mathrm{ns}}}^{\pm}\right| + \left|v_{\tilde{s}}^{-} - v_{\widetilde{\mathrm{ns}}}^{-}\right| + \left|v_{\tilde{s}}^{+} - v_{\widetilde{\mathrm{ns}}}^{\pm}\right| \tag{21}$$

Step 8: Determine relative assessment matrix (*RA*): Using ED and HD values for each alternative, the RA matrix is obtained using the following formula: where $\mathrm{RA} = \left[p_{it}\right]_{n\times n}$

$$p_{it} = (\mathrm{ED}_i - \mathrm{ED}_t) + \partial(\mathrm{ED}_i - \mathrm{ED}_t) * (\mathrm{HD}_i - \mathrm{HD}_t) \quad (22)$$

$$\partial(x) = \begin{cases} 1 & |x| \geq \rho \\ 0 & |x| < \rho \end{cases} \quad (23)$$

where $\partial \in \{1, 2, \ldots, n\}$, the threshold value ($\rho$) of ∂ function can be decided by DMs. In this study, ρ value is selected between 0.01–0.5 by DM.

Step 9: Compute the assessment score (AS) for each alternative: Assessment score of each alternative can be computed as stated in Eq. (24).

$$\mathrm{AS}_i = \sum_{t=1}^{n} p_{it} \quad (24)$$

Step 10: Rank alternatives: Alternatives are prioritized in the descending order based on their assessment scores. Considering results, the most suitable alternative is one with the highest assessment score.

5 Case Study

The steps of the proposed approach are illustrated through the following real-life case study.

5.1 Problem Definition

The objective of this research is to determine the most appropriate public transportation system among alternatives to transfer students, academicians, visitors, and university personnel along the campus. Accordingly, the statistics on the usage of public transportation on campus are given in Table 3. Total number of users of public transportation system is more than 36,000. Improved vehicular connection within the campus location is a need because of a wide campus area of the university considered. Figure 2 shows the campus area where the public transportation system is selected for.

The aims of the study consist the following issues:

- improve vehicular connection between the buildings of the university within the campus area in a metropolitan city in Turkey,
- suggest a safer and faster transportation system for passengers, who mostly are faculty, staff and students, and
- provide a long-term plan and sustainability for transportation mode of traveling.

As the methodology, a novel approach, which integrates IVIF-AHP and CODAS methods, is proposed to select the most sustainable public transportation system. The general scheme of the proposed method is displayed in Fig. 1. After defining the problem, related criteria and decision alternatives were determined based on DMs' opinions, and a questionnaire was produced to determine the weights of criteria using AHP under IVIF environment.

The questionnaire is conducted by a multi-disciplinary committee which consists of experts/DMs from the Departments of Architecture, Urban and Regional Planning, Mechanical Engineering, and Environmental Engineering. The experts are not only evaluators but also the users of the campus transportation system. The questionnaire is designed in a way to be able to implement a pairwise comparison of

Table 3 The users of public transportation system on Campus

Faculty of	Undergraduate student	Graduate student (MSc & Ph.D.)	Total student	Academic staff	Administrative staff	Staff (other)	Total
Education	2191	822	3013	106	20	9	3148
Electrical & Electronics	3574	1646	5220	165	25	14	5424
Arts & Science	3014	1193	4207	300	38	15	4560
Economic and Admin. Sc.	2175	1416	3591	111	22	6	3730
Civil Engineering	3110	1111	4221	167	34	16	4438
Chem. & Metal. Eng.	3678	881	4559	150	33	10	4752
Art & Design	675	218	893	66	15	4	978
School of Foreign Languages	7717	–	7717	167	12	7	7903
						Total:	34,933
Pedagogic formation	Student: 2397		Teknopark		Worker	7188	
Housing	# of flats: 499	# of habitant ∼ 1500	Average vehicle density daily			∼ 600	
Teknopark	Worker 7188						

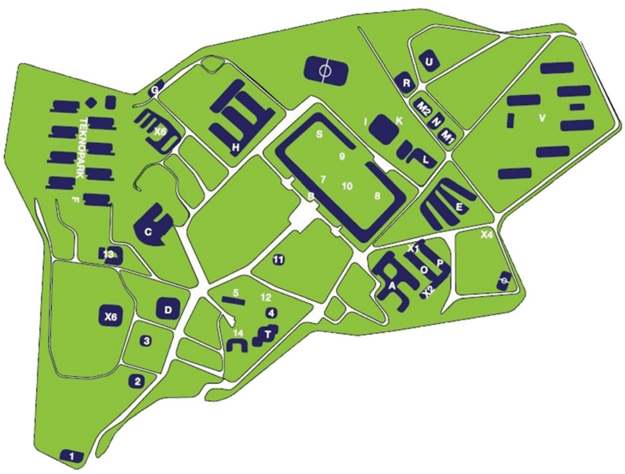

Fig. 2 The campus area map

criteria and alternatives. Evaluation criteria are determined as follows: financial Impact (*F*) consists of investment cost (*F*1), operational cost (*F*2), economic life (*F*3), capacity (F4), and functionality (*F*5); Environmental awareness (*E*) is composed of vehicle noise and vibrations (*E*1), environmental susceptibility (*E*2), comfort (*E*3), and usability for disabled people (*E*4); ease of use (EU) consists of accessibility (EU1), parking lot (EU2), and vehicle frequency (EU3); safety (*S*) consists of safety of vehicles (*S*1), breakdown frequency (*S*2), and ease of maintenance (*S*3); and technical conditions (*T*) consists of type of feeder (*T*1), Terrain suitability (*T*2), and visual design of vehicle (*T*3).

On the other hand, the determined alternatives for campus transportation are as follows: personal rapid transit (PRT) consists small-sized automated vehicles, which lift public on predetermined guideways. PRT is a special type of automated guideway transit. In an automated guideway transit (AGT), all vehicles are fully automated which means vehicles move without drivers on a guided way. Battery electric bus (BAT. ELECTR. BUS), a type of electric bus, is used in public transportation as well. BAT. ElECTR. BUS gets its energy from an on board battery. As a railway transportation, Trams (TRAM) are used as one of the public transportation modes in several country. Tram moves on tracks of a railway along the city. The structure of the decision hierarchy is represented in Fig. 3.

The application procedure of the proposed approach is as follows:

Step 1: Invite DMs to construct pairwise decision-making matrix using IVIF sets: Twenty experts are invited to make judgements on criteria and sub-criteria using linguistic variables. Saaty's [49] consistency procedure is applied to each DMs' pairwise comparison matrix using the related scores of classical AHP method for linguistic scales as shown in Table 4. The consistency ratio should be smaller than 0.1 for a matrix to be considered as consistent.

Step 2: Build IVIF aggregated pairwise matrix for criteria and sub-criteria: Once the consistency ratios of each pairwise matrix are calculated, they are transformed into IVIF numbers using the scale given in Table 1. Equation (6) should be applied to obtain IVIF aggregated pairwise matrix. For the sake of simplicity and readability, in this paper, we only present the aggregated pairwise decision matrix for five main criteria (see Table 5) which are created based on 20 DMs' opinions. DMs' weights for each engineer, and architect and planner are used as 0.06 and 0.04, respectively.

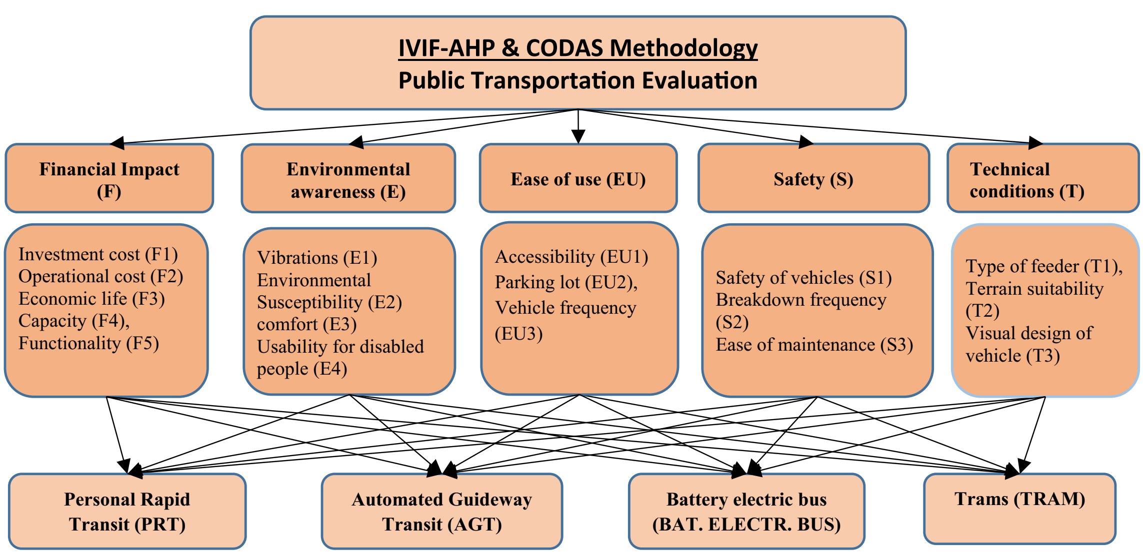

Fig. 3 Decision hierarchy of public transportation system evaluation

Table 4 Linguistic terms and corresponding crisp number

Linguistic term	Crisp number
Absolutely Low (AL)	0.11
Very Low (VL)	0.14
Low (*L*)	0.2
Medium Low (ML)	0.33
Exactly (EE)	1
Medium High (MH)	3
High (*H*)	5
Very High (VH)	7
Absolutely High (AH)	9

Step 3: Generate the score judgment and the interval multiplicative matrices: The score judgment and the interval multiplicative matrices are obtained using the steps of IVIF-AHP. The interval multiplicative matrix for score judgments of main criteria is given in Table 6.

Step 4: Calculate global weights of sub-criteria: To tabulate the weights of criteria and sub-criteria, IVIF-AHP method is applied and global weights are gained as in Table 7. The crisp weights are obtained by applying defuzzification formula given in Eq. (5).

Step 5: Form aggregated IVIF decision matrix: Each DM expresses their opinion about transportation alternatives considering main and sub-criteria. All the individual decision matrices are aggregated by applying the IVIFHG operator given in Eq. (6). The aggregated decision matrix based on 20 expert opinions in the form of IVIF numbers is shown in Table 8.

Step 6: Normalize the aggregated evaluation matrix: The normalized values of the aggregated decision matrix are computed using Eq. (12).

Step 7: Construct the weighted normalized IVIF decision matrix: Crisp weights obtained from the previous stage (IVIF-AHP) are multiplied by normalized matrix using Eq. (13) with the help of Eq. (2). The weighted normalized IVIF decision matrix is shown in Table 9.

Step 8: Tabulate fuzzy negative solution values: The negative ideal solution for each alternative is determined by using Eq. (14–17). Table 10 shows the negative ideal solutions for the alternatives.

Step 9: Calculate ED and HD values for each alternative considering negative ideal solution: ED and HD values of alternatives are calculated using Eq. (18–21). The alternative which has greater distances from the negative ideal solution is more desirable. The calculated ED and HD values of alternatives from the negative ideal solution are shown in Table 11.

Table 5 The aggregated pairwise comparison matrix for main criteria

	F				*E*				EU				*S*				*T*			
	μ^L	μ^U	ν^L	ν^U	μ^L	μ^U	ν^L	ν^U	μ^L	μ^U	ν^L	ν^U	μ^L	μ^U	ν^L	ν^U	μ^L	μ^U	ν^L	ν^U
F	0.500	0.500	0.500	0.500	0.400	0.472	0.459	0.528	0.416	0.498	0.411	0.491	0.239	0.336	0.544	0.635	0.414	0.487	0.413	0.493
E	0.410	0.481	0.448	0.519	0.500	0.500	0.500	0.500	0.482	0.566	0.343	0.434	0.359	0.441	0.481	0.559	0.498	0.563	0.374	0.437
EU	0.370	0.454	0.459	0.546	0.289	0.387	0.515	0.613	0.500	0.500	0.500	0.500	0.238	0.332	0.569	0.668	0.395	0.477	0.429	0.523
S	0.546	0.624	0.298	0.376	0.471	0.544	0.387	0.456	0.574	0.641	0.295	0.359	0.500	0.500	0.500	0.500	0.574	0.636	0.305	0.364
T	0.392	0.467	0.459	0.533	0.313	0.399	0.523	0.601	0.406	0.486	0.423	0.514	0.235	0.328	0.584	0.672	0.500	0.500	0.500	0.500

Table 6 Interval multiplicative matrix for score judgment matrix of main criteria

	F		*E*		EU		*S*		*T*	
F	1	1	0.744	1.03	0.842	1.222	0.401	0.619	0.834	1.185
E	0.777	1.079	1	1	1.117	1.67	0.631	0.911	1.151	1.546
EU	0.666	0.988	0.474	0.744	1	1	0.372	0.58	0.745	1.116
S	1.479	2.118	1.034	1.432	1.637	2.216	1	1	1.619	2.144
T	0.723	1.02	0.516	0.752	0.779	1.157	0.366	0.554	1	1

Table 7 Global weights of sub-criteria

Main criteria	Sub-criteria	Aggregated
Financial impact (*F*) 0.1776	Investment cost (*F*1)	0.031
	Operational cost (*F*2)	0.036
	Economic life (*F*3)	0.035
	Capacity (*F*4)	0.044
	Functionality (*F*5)	0.031
Environmental awareness (*E*) 0.2227	Vehicle noise and vibrations (*E*1)	0.053
	Environmental susceptibility (*E*2)	0.063
	Comfort (*E*3)	0.033
	Usability for disabled people (*E*4)	0.074
Ease of Use (EU) 0.1524	Easy access (EU1)	0.068
	Assigned spaces for car parking (EU2)	0.027
	Vehicle frequency (EU3)	0.057
Safety (*S*) 0.2914	Safety of vehicles (*S*1)	0.146
	Breakdown frequency (*S*2)	0.075
	Ease of service or maintenance (*S*3)	0.071
Technical conditions (*T*) 0.1559	Type of feeder (*T*1)	0.051
	Terrain suitability (*T*2)	0.06
	Visual design (*T*3)	0.045

Step 10: Construct RA matrix: The RA matrix is obtained via Eqs. (22–23) using ED and HD values given in Table 12.

Step 11: Compute the assessment score (AS) of each alternative: The AS of each alternative is calculated using Eq. (24). The AS of each alternative is shown in Table 12.

Step 12: Prioritize the alternatives: On the basis of AS, prioritize the alternatives in accordance with the descending order of assessment scores. The alternative having the highest AS is the best option among the alternatives. The results are shown in Table 12. The calculated AS values show that the alternatives are prioritized as: BAT.ELECTR.BUS $\succ$ TRAM $\succ$ AGT $\succ$ PRT

Therefore, we should select the battery electric bus as the best alternative with respect to the assessments performed by the IVIF-AHP & CODAS method.

5.2 Sensitivity Analysis

In this study, sensitivity analysis is conducted to verify the stability and validity of the proposed framework with respect to five cases or scenarios. Since the weights provided by DMs significantly can affect the rank, the change of weights should be assessed. Accordingly, on the basis of different weights of DMs considering their proficiency, the ranking of alternatives is analyzed. The weights assigned to DMs are shown in Table 13 for each scenario. Results of sensitivity analysis for each DMs weights are compared as shown in Fig. 4a. Applying different weights concluded the same rankings, which show the stability and validity of the proposed method. Then, the sensitivity analysis is applied for different threshold value (ρ) to verify the robustness and validity of the proposed approach. The results are shown in Table 14 and Fig. 4b. Accordingly, the results are similar except in Case 7. The proposed results prove that

Table 8 Aggregated decision matrix in the form of IVIF numbers

	AGT				TRAM				BAT. ELECTR. BUS				PRT			
	μ^L	μ^U	v^L	v^U	μ^L	μ^U	v^L	v^U	μ^L	μ^U	v^L	v^U	μ^L	μ^U	v^L	v^U
*F*1	0.383	0.49	0.416	0.51	0.153	0.312	0.535	0.688	0.452	0.516	0.43	0.476	0.517	0.63	0.262	0.37
*F*2	0.385	0.47	0.461	0.53	0.11	0.268	0.581	0.732	0.486	0.576	0.342	0.413	0.485	0.572	0.349	0.428
*F*3	0.451	0.519	0.424	0.481	0.328	0.43	0.487	0.57	0.472	0.587	0.304	0.406	0.366	0.505	0.368	0.495
*F*4	0.502	0.55	0.41	0.45	0.155	0.328	0.526	0.672	0.486	0.535	0.423	0.458	0.423	0.576	0.279	0.424
*F*5	0.464	0.602	0.264	0.398	0.288	0.418	0.474	0.582	0.489	0.52	0.453	0.476	0.504	0.553	0.404	0.447
*E*1	0.383	0.491	0.417	0.509	0	0.186	0.657	0.814	0.114	0.277	0.57	0.71	0.233	0.38	0.482	0.62
*E*2	0.329	0.452	0.436	0.548	0.494	0.644	0.206	0.356	0.515	0.602	0.318	0.377	0.48	0.63	0.219	0.37
*E*3	0.472	0.552	0.378	0.448	0.562	0.712	0.138	0.288	0.466	0.576	0.322	0.419	0.564	0.696	0.175	0.304
*E*4	0.429	0.519	0.403	0.481	0.348	0.48	0.4	0.52	0.42	0.544	0.339	0.44	0.522	0.634	0.259	0.366
EU1	0.441	0.524	0.404	0.476	0.359	0.46	0.457	0.54	0.48	0.605	0.276	0.387	0.459	0.548	0.376	0.452
EU2	0.487	0.556	0.383	0.444	0.521	0.597	0.336	0.403	0.498	0.574	0.357	0.411	0.496	0.646	0.204	0.354
EU3	0.362	0.511	0.346	0.489	0.414	0.525	0.377	0.475	0.463	0.571	0.328	0.411	0.481	0.632	0.218	0.368
*S*1	0.545	0.696	0.153	0.304	0.563	0.695	0.179	0.305	0.467	0.586	0.301	0.409	0.617	0.768	0.089	0.232
*S*2	0.316	0.432	0.468	0.568	0.115	0.272	0.576	0.728	0.361	0.456	0.465	0.537	0.454	0.542	0.379	0.458
*S*3	0.39	0.488	0.427	0.512	0.084	0.243	0.604	0.757	0.483	0.541	0.409	0.452	0.449	0.538	0.383	0.462
*T*1	0.198	0.347	0.509	0.653	0.311	0.444	0.432	0.556	0.465	0.521	0.432	0.473	0.383	0.463	0.473	0.537
*T*2	0.291	0.42	0.484	0.58	0.281	0.436	0.427	0.564	0.498	0.615	0.273	0.373	0.366	0.467	0.449	0.533
*T*3	0.474	0.504	0.472	0.496	0.501	0.539	0.429	0.461	0.464	0.589	0.29	0.403	0.523	0.663	0.199	0.337

Table 9 The weighted normalized IVIF decision matrix

	AGT				TRAM				BAT. ELECTR. BUS				PRT			
	μ^L	μ^U	v^L	v^U	μ^L	μ^U	v^L	v^U	μ^L	μ^U	v^L	v^U	μ^L	μ^U	v^L	v^U
*F*1	0.016	0.022	0.972	0.978	0.005	0.012	0.98	0.988	0.02	0.024	0.973	0.976	0.023	0.032	0.958	0.968
*F*2	0.02	0.027	0.969	0.973	0.005	0.014	0.978	0.986	0.027	0.036	0.958	0.964	0.027	0.035	0.958	0.965
*F*3	0.021	0.025	0.97	0.975	0.014	0.019	0.975	0.981	0.022	0.031	0.959	0.969	0.016	0.024	0.966	0.976
*F*4	0.033	0.038	0.958	0.962	0.008	0.02	0.97	0.98	0.032	0.037	0.959	0.963	0.026	0.041	0.942	0.959
*F*5	0.019	0.028	0.96	0.972	0.01	0.016	0.977	0.984	0.02	0.022	0.976	0.978	0.021	0.024	0.973	0.976
*E*1	0.034	0.049	0.941	0.951	0	0.017	0.972	0.983	0.009	0.026	0.963	0.974	0.019	0.036	0.951	0.964
*E*2	0.022	0.033	0.953	0.967	0.039	0.057	0.911	0.943	0.042	0.053	0.937	0.947	0.037	0.055	0.914	0.945
*E*3	0.015	0.019	0.976	0.981	0.021	0.031	0.946	0.969	0.015	0.02	0.971	0.98	0.021	0.029	0.953	0.971
*E*4	0.036	0.046	0.942	0.954	0.027	0.041	0.941	0.959	0.036	0.05	0.932	0.95	0.048	0.063	0.913	0.937
EU1	0.036	0.046	0.944	0.954	0.028	0.038	0.951	0.962	0.042	0.058	0.92	0.942	0.038	0.049	0.939	0.951
EU2	0.014	0.017	0.979	0.983	0.016	0.019	0.976	0.981	0.015	0.018	0.978	0.982	0.015	0.022	0.963	0.978
EU3	0.021	0.033	0.948	0.967	0.025	0.034	0.953	0.966	0.03	0.041	0.947	0.959	0.032	0.047	0.925	0.953
*S*1	0.079	0.11	0.806	0.89	0.082	0.082	0.888	0.888	0.06	0.079	0.881	0.921	0.099	0.138	0.75	0.862
*S*2	0.034	0.051	0.935	0.949	0.011	0.03	0.953	0.97	0.04	0.055	0.935	0.945	0.052	0.069	0.918	0.931
*S*3	0.042	0.058	0.93	0.942	0.008	0.026	0.959	0.974	0.057	0.068	0.926	0.932	0.05	0.066	0.921	0.934
*T*1	0.013	0.026	0.962	0.974	0.022	0.035	0.953	0.965	0.036	0.043	0.952	0.957	0.028	0.037	0.957	0.963
*T*2	0.02	0.031	0.959	0.969	0.019	0.019	0.924	0.924	0.04	0.055	0.927	0.945	0.026	0.036	0.954	0.964
*T*3	0.023	0.025	0.973	0.975	0.025	0.028	0.969	0.972	0.023	0.032	0.954	0.968	0.028	0.039	0.939	0.961

Table 10 The negative ideal solutions of alternatives

Alternatives	μ^U	v^L	v^U	μ^L
TRAM	0.005	0.012	0.98	0.988
TRAM	0.005	0.014	0.978	0.986
TRAM	0.014	0.019	0.975	0.981
TRAM	0.008	0.02	0.97	0.98
TRAM	0.01	0.016	0.977	0.984
TRAM	0	0.017	0.972	0.983
AGT	0.022	0.033	0.953	0.967
AGT	0.015	0.019	0.976	0.981
TRAM	0.027	0.041	0.941	0.959
TRAM	0.028	0.038	0.951	0.962
AGT	0.014	0.017	0.979	0.983
AGT	0.021	0.033	0.948	0.967
BAT. ELECTR. BUS	0.06	0.079	0.881	0.921
TRAM	0.011	0.03	0.953	0.97
TRAM	0.008	0.026	0.959	0.974
AGT	0.013	0.026	0.962	0.974
AGT	0.02	0.031	0.959	0.969
AGT	0.022	0.024	0.973	0.975

Table 11 Hamming and Euclidian distances of alternatives

	ED	HD
AGT	4.754	3.553
TRAM	4.840	3.554
BAT. ELECTR. BUS	4.877	3.678
PRT	4.767	3.333

the proposed approach is robust and efficient to deal with MCDM problems.

5.3 Comparative Analysis of the Proposed Approach

In this subsection, to demonstrate the superiority of the proposed method, the outcomes of the proposed method, Fuzzy CODAS developed by Ghorabaee et al. [50] and Crisp CODAS developed by Manoj and Sahu [51], are compared. The same data of public transportation system selection problem are adopted in the use of methods proposed by Ghorabaee et al. [50] and Manoj and Sahu [51] and Roy et al. [5]. To obtain crisp values, IVIF preference values are defuzzified using Eq. 6. Accordingly, the ranking results of the proposed method and existed methods are presented in Table 15. Even though Crisp AHP & CODAS and Fuzzy AHP & CODAS methods generate the same ranking results between alternatives, the proposed method and IVIF-CODAS present a different outranking (see Table 15). The comparison of the results based on different methods is shown in Fig. 5.

Since the representation abilities of IVIF numbers, ordinary FNs, and crisp numbers are different, expecting different outranking is reasonable. The main reason is that while the IVIF uses the intervals to express the membership and the non-membership degree to cope with uncertainty, the FNs uses only crisp numbers to express the membership degree, and the crisp numbers neglect the

Table 12 Relative assessment matrix, and the rank of the alternatives based on comparative analysis

	Relative assessment					Rank
	AGT	TRAM	BAT. ELECTR. BUS	PRT	AS	Proposed Method
AGT	0	− 0.087	− 0.247	− 0.012	− 0.347	3
TRAM	0.087	0	− 0.16	0.298	0.226	2
BAT ELECTR BUS	0.247	0.16	0	0.458	0.864	1
PRT	0.012	− 0.298	− 0.458	0	− 0.744	4

Table 13 Sensitivity analysis for the effect of DM‘s weights

Scenario	Weight		Alternative ranks
	DM (engineers)	DM (architects and planners)	
Scenario 1	0.1	0.9	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Scenario 2	0.2	0.8	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Scenario 3	0.3	0.7	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Scenario 4	0.4	0.6	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Scenario 5	0.5	0.5	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Scenario 6	0.6	0.4	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Scenario 7	0.7	0.3	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Scenario 8	0.8	0.2	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Scenario 9	0.9	0.1	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT

Table 14 Sensitivity analysis for the effect of ρ

Case	ρ	Alternative ranks
Case 1	0.01	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Case 2	0.02	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Case 3	0.03	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Case 4	0.04	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Case 5	0.05	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Case 6	0.1	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Case 7	0.2	BAT.ELECTR.BUS ≻ TRAM ≻ PRT ≻ AGT.
Case 8	0.3	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT
Case 9	0.4	BAT.ELECTR.BUS ≻ TRAM ≻ AGT ≻ PRT

Table 15 Rank of the alternatives based on comparative analysis

	RANK			
	Proposed method	Fuzzy AHP & CODAS	Crisp AHP & CODAS	IVIF-CODAS
AGT	3	3	3	3
TRAM	2	1	1	2
BAT ELECTR BUS	1	2	2	1
PRT	4	4	4	4

uncertainty of DMs judgments. Therefore, in terms of the ability of representing hesitancy and fuzziness of DMs, IVIF numbers are more dominance to FNs and crisp numbers. Considering superiority of the IVIF numbers to ordinary fuzzy numbers and crisp values, applying IVIF numbers to real-life problems is more suitable in order to cope with DMs hesitancy. Thus, the proposed approach offers a more effective and reasonable results to manage MCDM problems since the information gained from DMs may be defined in different dimensions.

6 Conclusions and Further Study Suggestions

The objective of this study is to model a transportation decision-making process which combines AHP and CODAS methods using IVIF sets to determine the most suitable transportation alternative within a university campus in a metropolitan city of Turkey considering key factors for sustainable public transportation. To handle uncertainty and hesitancy in the constructed decision-making process, both membership and non-membership

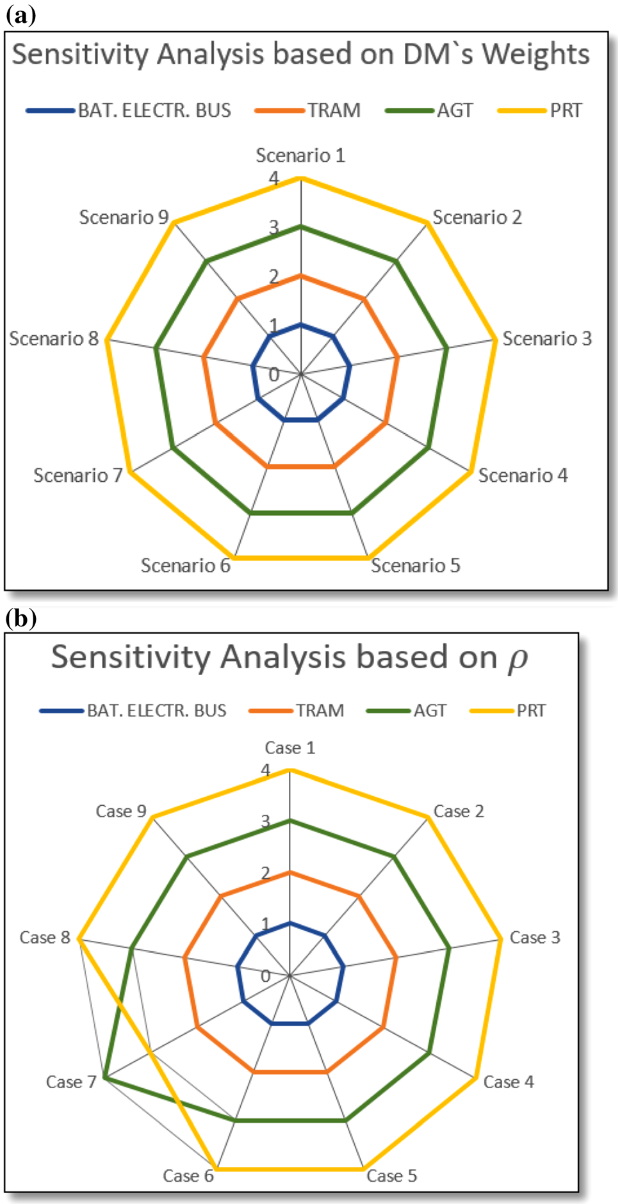

Fig. 4 Ranking of alternatives considering DM's weights (**a**) and the sensitivity analysis according to ρ (**b**)

functions are used by means of IVIF sets. In the proposed method, IVIF-AHP is used for determining the weights of the criteria, and CODAS for comparing the alternatives. To the best of authors' knowledge, it is the first time to use an integrated IVIF-AHP & CODAS method for prioritizing transportation alternatives.

According to the results, battery electric bus is determined as the most desirable public transportation alternative with respect to all recognized criteria, especially sustainability in environmental susceptibility, passenger comfort, and vehicles' safety. The final ranking of the transport alternatives that is obtained via IVIF-AHP & CODAS methods is as BAT. ELECTR. BUS ≻ TRAM ≻ AGT ≻ PRT. Since battery electric bus is determined as the best public transportation alternative for university campus, purchasing battery electric bus is recommended to the university managers and DMs. Consequently, since, the results were satisfactory and parallel to managers' expectations, they decided to purchase battery electric buses. In addition, sensitivity analysis and comparative analysis prove the robustness and feasibility of the proposed approach.

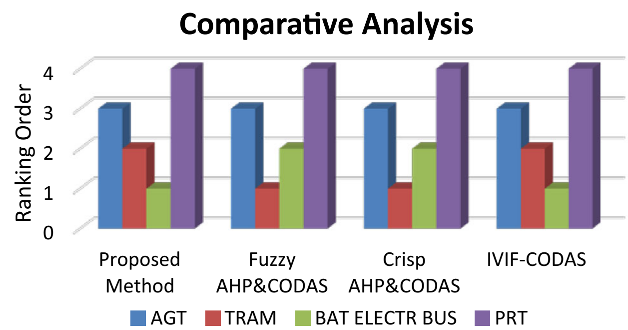

Fig. 5 Results of comparative analysis

On the other hand, there are some limitations of this study that should be highlighted. The response rate of the survey was less than the expected. As a future work, the proposed approach can be applied to any problem which aims to select the public transportation mode or vehicle for a specific region or county taking the importance of the objectives and policies into account. Finally, as another future work, comparison with other MCDM methods is suggested.

Author Contribution SS involved in methodology discussion and analysis. NA participated in content planning, sensitivity analysis, and manuscript writing and editing.

Compliance with Ethical Standards

Conflict of Interests On behalf of all authors, the corresponding author states that there is no conflict of interest.

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