Soft Computing (2023) 27:2325–2345
https://doi.org/10.1007/s00500-022-07707-3

FUZZY SYSTEMS AND THEIR MATHEMATICS

Evaluation of the route selection in international freight transportation by using the CODAS technique based on interval-valued Atanassov intuitionistic sets

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Accepted: 26 November 2022 / Published online: 21 December 2022

Abstract

The selection of a proper international freight transport route is one of the crucial tasks for decision-makers since it can affect costs, efficiency, and transportation performance. Besides, the selection of suitable and appropriate freight routes can also reduce external costs of transportation such as emissions, noise, traffic congestions, accidents, and so on. Route selection in international transportation is a complicated decision-making problem as many conflicting factors and criteria affect the assessment process. It has been observed that there is no mathematical model and methodological frame used for solving these selection problems, and decision-makers make decisions on this issue based on their own experiences and verbal judgments in the research process. Therefore, a methodological frame is required to make rational, realistic, and optimal decisions on route selection. From this perspective, the current paper proposes using the IVAIF CODAS, an extended version of the traditional CODAS techniques, and using the Atanassov interval-valued intuitionistic fuzzy sets (IVAIFS) for processing better the existing uncertainties. The proposed model is applied to solve the route selection, a real-life decision-making problem encountered in international transportation between EU countries and Turkey. According to the results of the analysis, option A6 (i.e., Route-6 (Bursa–Istanbul–Pendik–Trieste (Ro-Ro)–Austria–Frankfurt/Germany) has been determined as the best alternative. These obtained results have been approved by a comprehensive sensitivity analysis performed by using different MCDM techniques based on interval-valued intuitionistic fuzzy sets. Hence, it can be accepted that the proposed model is an applicable, robust, and powerful mathematical tool; also, it can provide very reliable, accurate, and reasonable results. As a result, the proposed model can provide a more flexible and effective decision-making environment as well as it can provide valuable advantages to the logistics and transport companies for carrying out practical, productive, and lower cost logistics operations.

Keywords Interval-valued intuitionistic fuzzy sets · Codas · Route selection · Logistics · International freight transportation · Multi-criteria group decision-making

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1 Introduction

Growth in global trade was recorded at 4.9% in 2020 by International Monetary Fund. According to estimations by IMF, in 2021, global growth is projected at 5.4% because the COVID-19 pandemic has had a more negative impact on economic activities in the first half of 2020 than anticipated. The recovery in international trade and economy will be gradual (IMF 2020). Based on these kinds of developments, demands on freight transport activities have shown increases. Freight was transported on over 1.7 trillion kilometers across Europe's roads, and 74% of it has been carried with articulated trucks with gross weights of over 33 tones. It is seen that road freight transport mode still dominates international and domestic freight transportation, and its share has reached 75% by increasing 2.8% annually (EEA 2021). It has also caused some problems such as external transportation costs (i.e., energy consumption, environmental impacts, accidents, noise, and so on). According to some reports on the environmental impacts of transportation published by international institutions, heavy vehicles used in freight transport activities in the EU-28 are currently responsible for 27% of road transport carbon dioxide (CO_2) emissions, and emissions have increased 25% since 1990. In addition to environmental impacts, road freight transport is responsible for additional energy consumption in EU-28. Road transport accounts for the most significant energy consumption in the transport sector, accounting for 73% of the total demand (EEA 2021). Besides, road freight transport can cause some negative impacts such as traffic congestion, accidents, and noise on the economy and society. When these are considered, the solutions reducing the share of the road transportation can provide valuable advantages for reducing emissions sourcing from road freight transportation.

However, selecting a proper transportation route is highly complex and time-consuming; many uncertainties affect the evaluation processes. Because of that, classical and traditional techniques such as AHP (Kengpol et al. 2014) and TOPSIS may not solve these kinds of problems, and their contributions to both the literature and real-life about this issue are limited. The previous studies existing in the literature can be summarized as follows: Some papers dealt with the route selection for special cargo transportation such as dangerous goods (Jassbi and Makvandi 2010; Lim and Desai 2010; Jiang and Ying 2014), perishable foods, Out of Gauge cargo (Meng et al. 2017; Randolph 1991; Petraška and Palšaitis 2012); and they naturally focused on safety and security as the essential factors. Bandeira et al. (2013) examined route selection processes considering the environmental impacts of transport operations. They proposed faster routes to reduce both fuel use and CO_2 emissions. The most important part of the previous studies focused on determining the best route option, which focused on intermodal and combined transport modes (Wang and Yeo 2018; Chang 2008; Tiwari et al. 2013; Ashraf et al. 2022). Besides, almost all of them determined the transport cost criterion as the most crucial factor. According to their findings, some criteria such as reliability, transportation capability, total time, and security followed it. Some previous studies suggested some techniques by focusing on costs (Michell and Gu 2004), safety, speed, etc. Some of these techniques are the genetic algorithm (Jassbi and Makvandi 2010), mixed-integer linear programming (MILP) approach (Tiwari et al. 2013), artificial neural network (ANN) theory (Qu and Chen, 2008), and the Grey Relational Analysis method (Yu et al. 2005). Some papers also examined the route selection problems without using a mathematical model (Huynh and Fotuhi 2013; Bookbinder and Fox 1998; Marín-Tordera et al. 2006; Kaewfak and Ammarapala 2018; Boardman et al. 1997; Pham et al. 2018; Sicilia et al. 2014).

Although these papers are interesting and have provided contributions to the literature, their contribution and applicability are limited. Ignoring the uncertainties that affect the decisions related to route selection is the most important reason for that. Secondly, each decision-maker may not have experience, competency, and knowledge about route selection in international freight transportation, and some may have to decide with insufficient information. Hence, the applicability of techniques suggested by these previous studies is weak since they did not consider special conditions related to decision-makers.

From this perspective, the most critical issue is determining the optimal and suitable transport route among all existing alternatives under the highly complicated and existing many ambiguities and conflicting criteria. Thus, the main aim of the current paper is to present a practical and systematic framework providing a flexible group decision-making environment by considering the special features of the decision-makers (i.e., experiences, competencies, knowledge levels, and abilities). The current paper proposes to use the Interval-Valued Atanassov Intuitionistic Fuzzy CODAS (IVAIF CODAS) as a methodological frame to fill the gaps existing in the literature practitioners and decision-makers who are responsible for selecting an appropriate route in the field of logistics and transportation industry. We preferred to apply this approach, as it is impossible to collect accurate and reliable crisp data; in addition, crisp values for some data may not exist in some situations. COmbinative Distance-based ASsessment (CODAS) technique is a very novel and robust method, and it has been applied in some studies in the literature (Ghorabaee et al. 2016; Badi et al. 2022; Tuş and Adalı 2018; Panchal et al. 2017). According to this method, two types of distances, which are called Euclidean distance (ED) and Taxicab distance (TD), are used to evaluate the desirability of alternatives (Deveci et al. 2020). In addition, some papers using the CODAS technique based on the fuzzy sets are available in the existing literature, and some of them, which are interesting, are summarized in Table 1.

When these papers are evaluated in general, it can be seen that different effects of the cost and benefit criteria were not considered in some papers (Bolturk and Kahraman 2018). Moreover, there is no clarification in these papers on how the experts (decision-makers) were selected and how the selection criteria and decision options were determined in almost all studies. In addition to that, it is not clear that how evaluation for decision-makers was performed. The proposed IVAIF CODAS has the potential to solve these kinds of problems. Firstly, we determined a set of criteria for selecting the appropriate experts as follows: (1) being a highly experienced professional (at least 15 years' experience in the field of international transportation as a senior executive or company owner), (2) the members of the board of experts should be a member of the board of directors in a professional association of transportation and logistics, and (3) they should graduate from an undergraduate program. In addition to the annual turnover, the number of the annual transport operation conducted by their companies has been considered. By considering these factors, decision-makers were evaluated by researchers. Secondly, decision options and criteria were determined together with the members of the board of experts.

This paper can also contribute to the literature: (1) It has a basic algorithm that can be easily applicable by decision-makers responsible for making decisions about route selection. Therefore, the proposed model can help solve real-life decision-making problems and contribute to future studies in the academic field. (2) It is also suitable for real-life since the selection criteria, and decision options were determined together by highly experienced and knowledgeable professionals. These criteria and options can be used in future research and solve real-life decision-making problems. (3) Theoretical steps of the proposed model indicated in detail by applying the model for selecting the appropriate transport route in international freight transport between EU countries and Turkey to demonstrate the effectivity of the proposed approach in the evaluation process for solving decision-making problems encountered in real life. (4) The sensitivity analysis results validate the proposed model and prove that the suggested model was a practical approach.

This paper is organized into six sections. In the first section, the main problems, research questions, and the proposed solution are summarized. In the second section, the proposed model and its implementation steps are demonstrated. A numerical analysis has been performed in the third section. While the results are discussed in the fifth section, this study is concluded in the sixth section.

2 The proposed MCDM framework

This section expresses the suggested technique considering the Interval-Valued Atanassov Intuitionistic Fuzzy CODAS (IVAIF-CODAS) technique.

2.1 Preliminaries for interval-valued intuitionistic fuzzy sets

Here, some basic concepts and preliminaries relevant to Interval-Valued Intuitionistic Fuzzy Set (IVIFS) are presented.

Definition 1 (Atanassov and Gargov 1989): Let $X = \{x_1, x_2, x_3, \ldots, x_n\}$ be a non-empty set of the universe of discourse. An IVIFS $\widetilde{A}$ in X can be defined as:

Table 1 Some previous papers using the CODAS technique based on the fuzzy sets

Author	Application field	Technique
Ghorabaee et al. (2017)	Market segment evaluation	Fuzzy CODAS
Panchal et al. (2017)	Urea Fertilizer Industry	Fuzzy AHP + Fuzzy CODAS
Peng and Garg (2018)	Mine emergency	Interval-valued fuzzy soft sets
Bolturk (2018)	Supplier selection	Pythagorean Fuzzy CODAS
Bolturk and Kahraman (2018)	Wave energy facility location	IF intuitionistic fuzzy CODAS
Yeni and Özçelik (2018)	Personnel selection	IF intuitionistic fuzzy CODAS
Roy et al. (2019)	Material selection	Intuitionistic fuzzy CODAS
Seker (2020)	Investment project	Intuitionistic trapezoidal fuzzy CODAS
Deveci et al. (2020)	Renewable energy alternatives	IF intuitionistic fuzzy CODAS
Dahooie et al. (2020)	Cloud computing	IF intuitionistic fuzzy CODAS
Ouhibi and Frikha (2020)	Environmental quality	Fuzzy CODAS SORT

$$\widetilde{A} = \left\{\left(x_i\left[\mu^L_{\underset{A}{\sim}}(x_i), \mu^R_{\underset{A}{\sim}}(x_i)\right], \left[v^L_{\underset{A}{\sim}}(x_i), v^R_{\underset{A}{\sim}}(x_i)\right]\right)|x_i \in X\right\}, \tag{1}$$

where $\left[\mu^L_{\underset{A}{\sim}}(x_i), \mu^R_{\underset{A}{\sim}}(x_i)\right]$ and $\left[v^L_{\underset{A}{\sim}}(x_i), v^R_{\underset{A}{\sim}}(x_i)\right]$ represent the intervals of membership and non-membership degrees of element $x_i \in \widetilde{A}$, respectively, gratifying $\mu^R_{\underset{A}{\sim}}(x_i) + v^R_{\underset{A}{\sim}}(x_i) \leq 1, 0 \leq \mu^L_{\underset{A}{\sim}}(x_i) \leq \mu^R_{\underset{A}{\sim}}(x_i) \leq 1$, and $0 \leq v^L_{\underset{A}{\sim}}(x_i) \leq v^R_{\underset{A}{\sim}}(x_i) \leq 1$ for all $x_i \in \widetilde{A}$.

$$\pi_{\underset{A}{\sim}}(x_i) = \left[1 - \mu^R_{\underset{A}{\sim}}(x_i) - v^R_{\underset{A}{\sim}}(x_i), 1 - \mu^L_{\underset{A}{\sim}}(x_i) - v^L_{\underset{A}{\sim}}(x_i)\right]$$

is defined as interval-valued Intuitionistic hesitancy degree of IVIFS $\widetilde{A}$. For each $x_i \in \widetilde{A}$, if $\mu^L_{\underset{A}{\sim}}(x_i) = \mu^R_{\underset{A}{\sim}}(x_i)$ and $v^L_{\underset{A}{\sim}}(x_i) = v^R_{\underset{A}{\sim}}(x_i)$, then $\widetilde{A}$ is reduced and IFS (Xu et al. 2015).

One of the geometrical interpretations for the intuitionistic fuzzy sets and for interval-valued intuitionistic fuzzy sets is given in (Atanassova 2010) and in (Atanassova and Angelova 2021), respectively.

The pair $\widetilde{\alpha} = \left(\mu_{\underset{\alpha}{\sim}}(x_i), v_{\underset{\alpha}{\sim}}(x_i)\right)$ an interval-valued intuitionistic fuzzy number (IVIFN) is defined by Xu (2007) described an IVIFN by $\widetilde{\alpha} = ([a, b], [c, d])$, where $[a, b] \subseteq [0, 1]$, $[c, d] \subseteq [0, 1]$,$b + d \leq 1$.

Definition 2 (Xu 2007; Xu et al. 2015): Let suppose there are three IVIFNs such as $\widetilde{\alpha}_1 = ([a_1, b_1], [c_1, d_1])$, $\widetilde{\alpha}_2 = ([a_2, b_2], [c_2, d_2])$, and $\widetilde{\alpha} = ([a, b], [c, d])$; thus.

(1) $(\widetilde{\alpha})^c = ([c, d], [a, b])$;
(2) $\widetilde{\alpha}_1 + \widetilde{\alpha}_2 = ([[a_1 + a_2 - a_1a_2, b_1 + b_2 - b_1b_2], c_1c_2, d_1d_2])$;
(3) $\lambda\widetilde{\alpha} = \left(\left[1 - (1 - a)^\lambda, 1 - (1 - b)^\lambda\right], \left[c^\lambda, d^\lambda\right]\right)$, $\lambda > 0$.

Definition 3 (Xu 2007; Xu et al. 2015): Let $\widetilde{\alpha}_j = \left(\left[a_j, b_j\right], \left[c_j, d_j\right]\right)$ and $j = (1, 2, 3, ..., n)$ be a set of IVIFNs. In a group decision-making environment, IVIFWA operator is used to aggregate the evaluations of the experts. The mathematical expression of the IVIFWA operator is presented in Eq. 2.

$$IVIFWA_\omega(\widetilde{\alpha}_1, \widetilde{\alpha}_2, ...\widetilde{\alpha}_n) = \sum_{j=1}^{n} \omega_j\widetilde{\alpha}_j, \tag{2}$$

where $\omega = (\omega_1, \omega_1, ..., \omega_n)^T$ is a weight vector of $\widetilde{\alpha}_j$ with each ω takes value between 0 and 1, and the sum of ω_j should be equal to 1.

Next, the aggregated value of the experts' evaluations is computed by applying the IVIFWA operator as follows:

$$\begin{aligned} &IVIFWA_\omega(\widetilde{\alpha}_1, \widetilde{\alpha}_2, ...\widetilde{\alpha}_n) \\ &= \left(\left[1 - \prod_{j=1}^{n}(1 - a_j)^{\omega_j}, 1 - \prod_{j=1}^{n}(1 - b_j)^{\omega_j}\right], \prod_{j=1}^{n} c_j^{\omega_j}, \prod_{j=1}^{n} d_j^{\omega_j}\right). \end{aligned} \tag{3}$$

Definition 4 (Xu 2007; Xu et al. 2015): Let $\widetilde{\alpha}_j = \left(\left[a_j, b_j\right], \left[c_j, d_j\right]\right)$ and $j = (1, 2, 3, ..., n)$ be a set of IVIFNs.

$$s(\widetilde{\alpha}) = \frac{1}{2}(a + b - c - d), \tag{4}$$

$$h(\widetilde{\alpha}) = \frac{1}{2}(a + b + c + d) \tag{5}$$

where $s(\widetilde{\alpha})$ denotes score function and $h(\widetilde{\alpha})$ is the accuracy function of IVIFN $\widetilde{\alpha}$. $s(\widetilde{\alpha}) \in [-1, 1]$ is defined as membership degree and $h(\widetilde{\alpha}) \in [0, 1]$ is the accuracy degree. As the score function may take negative values $[-1, 1]$, when they are aggregated with the linear weighted aggregation approach. Thus, the score function is normalized to take positive value between 0 and 1. Given a variable $y \in [-1, 1]$, if it is defined as

$$f(y) = \frac{y + 1}{2}, \tag{6}$$

it retains the variable y' monotonicity aside from it also maps y for [0,1]. Thus, the score function is modified by following the basic procedure of definition 4 and the new score function of IVIFN $\widetilde{\alpha}$ is defined.

Definition 5a (Xu 2007; Xu et al. 2015): Suppose $\widetilde{\alpha} = ([a, b], [c, d])$ be an IVIFN. The normalized score function is computed as follows

$$s^*(\widetilde{\alpha}) = \frac{1}{2}(s(\widetilde{\alpha}) + 1) \tag{7}$$

where $s(\widetilde{\alpha}) = \frac{1}{2}(a + c + b - d)$, Definitely, $s^*(\widetilde{\alpha}) \in [0, 1]$. $s(\widetilde{\alpha}) = \frac{1}{2}(a + c + b - d)$ and $j = (1, 2, 3, ..., n)$ be a set of IVIFNs.

Definition 5b (Xu 2007; Xu et al. 2015): Suppose $\widetilde{\alpha} = ([a, b], [c, d])$ be an IVIFN. The uncertainty function is calculated as follows

$$\gamma(\widetilde{\alpha}) = 1 - h(\widetilde{\alpha}) \tag{8}$$

where $h(\widetilde{\alpha}) = \frac{1}{2}(a + c + b + d)$.

Let suppose $\widetilde{\alpha} = ([a, b], [c, d])$ is an evaluation value of the route alternatives in freight transportation concerning the criterion $\widetilde{\alpha}$. Then, it is accepted that the normalized score function $(s(\widetilde{\alpha}))$ denotes the advantage, and the uncertainty function $(\gamma(\widetilde{\alpha}))$ is the disadvantage for the x alternative concerning the $\widetilde{\alpha}$ criterion. Thus, if $s(\widetilde{\alpha})$ is higher than $\gamma(\widetilde{\alpha})$, x alternatives can be defined as satisfactory and better.

Definition 6 (Xu and Chen 2007; Xu 2007): Suppose $\widetilde{\alpha}_1 = ([a_1, b_1], [c_1, d_1])$ and $\widetilde{\alpha}_2 = ([a_2, b_2], [c_2, d_2])$ are two different set of IVIFN. Some algebraic operations of $\widetilde{\alpha}_1$ and $\widetilde{\alpha}_2$ are performed as follows:

$$\widetilde{\alpha}_1 \bigcap \widetilde{\alpha}_2 = ([\min(a_1, a_2), \min(b_1, b_2)], [\max(c_1, c_2), \max(d_1, d_2)]) \tag{9}$$

$$\widetilde{\alpha}_1 \bigcup \widetilde{\alpha}_2 = ([\max(a_1, a_2), \max(b_1, b_2)], [\min(c_1, c_2), \min(d_1, d_2)]) \tag{10}$$

$$\widetilde{\alpha}_1 \oplus \widetilde{\alpha}_2 = ([a_1 + a_2 - a_1 a_2, b_1 + b_2 - b_1 b_2], [c_1 c_2, d_1 d_2]) \tag{11}$$

$$\widetilde{\alpha}_1 \otimes \widetilde{\alpha}_2 = ([a_1 a_2, b_1 b_2], [c_1 + c_2 -, c_1 c_2, d_1 + d_2 - d_1 d_2]) \tag{12}$$

$$\lambda \widetilde{\alpha}_1 = \left(\left[1 - (1 - a_1)^{\lambda}, 1 - (1 - b_1)^{\lambda}\right], \left[c_{_1}^{\lambda} + c_{_2}^{\lambda}\right]\right), \lambda > 0 \tag{13}$$

$$\widetilde{\alpha}_1^{\lambda} = \left(\left[a_1^{\lambda}, b_1^{\lambda}\right], \left[1 - (1 - c_1)^{\lambda}, 1 - (1 - d_1)^{\lambda}\right]\right), \lambda > 0, \tag{14}$$

$$\widetilde{\alpha}_1 - \widetilde{\alpha}_2 = \begin{cases} \left(\left[\frac{a_1 - a_2}{1 - a_2} - \frac{b_1 - b_2}{1 - b_2}\right], \left[\frac{c_1}{c_2}, \frac{d_1}{d_2}\right]\right) \\ \text{\textit{if} } a_1 \geq a_2, b_1 \geq b_2, c_1 \leq c_2, d_1 \leq d_2, \\ \text{and } c_2 > 0, a_2 \neq 1, b_2 \neq 1 \\ \text{and } c_1(1 - a_2) \leq, c_2(1 - a_1), \\ \text{and } d_1(1 - b_2) \leq, d_2(1 - b_1), \\ ([0, 0][1, 1]) \text{ otherwise} \end{cases} \tag{15}$$

$$\widetilde{\alpha}_1 \div \widetilde{\alpha}_2 = \begin{cases} \left(\left[\frac{a_1}{a_2}, \frac{b_1}{b_2}\right], \left[\frac{c_1 - c_2}{1 - c_2}, \frac{d_1 - d_2}{1 - d_2}\right]\right) \\ \text{\textit{if} } a_1 \leq a_2, b_1 \leq b_2, c_1 \geq c_2, d_1 \geq d_2, \\ \text{and } a_2 > 0, b_2 > 0, c_2 \neq 1, c_2, d_2 \neq 1 \\ \text{and } a_1(1 - c_2) \leq, a_2(1 - d_1), \\ \text{and } b_1(1 - d_2) \leq, b_2(1 - d_1), \\ ([0, 0][1, 1]) \text{ otherwise} \end{cases} \tag{16}$$

The operations described in Definitions 2 and 6 are modifications of these for intuitionistic fuzzy sets and for interval-valued intuitionistic fuzzy sets from Atanassov (1986) and Atanassov and Gargov (1989), respectively.

2.2 IVAIF CODAS

The Interval-Valued Atanassov Intuitionistic Fuzzy CODAS technique (IVAIF-CODAS) suggested in the current paper is an extended form of the CODAS technique. This technique has a basic algorithm consisting of eight implementation steps as follows: (Yeni and Özçelik 2019):

Step 1. Generate the IVAIF decision matrices. By collecting the linguistic evaluations of decision-makers, initial IVAIF decision matrices are formed as follows:

$$\widetilde{X}_l = \left[\widetilde{x}_{ijl}\right]_{n \times m} = \begin{bmatrix} \widetilde{x}_{11l} & \cdots & \widetilde{x}_{1ml} \\ \widetilde{x}_{21l} & \cdots & \widetilde{x}_{2ml} \\ \widetilde{x}_{n1l} & \cdots & \widetilde{x}_{xnl} \end{bmatrix} \tag{17}$$

$\widetilde{x}_{ijl}$ represents IVAFN of i^{th} alternative regarding j^{th} criterion and l^{th} decision-maker $(1 \leq l \leq e)$. After the linguistics evaluations performed by decision-makers are collected, these evaluations are converted to the IVAFN corresponding to the IVAF scale presented in Table 2. In addition, the weight values of the criteria are determined in this step.

$$\widetilde{W}_l = \left[\widetilde{w}_{jl}\right]_{1 \times m} = \begin{bmatrix} \widetilde{w}_{1l} \\ \vdots \\ \widetilde{w}_{ml} \end{bmatrix} \tag{18}$$

$\widetilde{w}_{jl}$ represents the evaluation j^{th} for a criterion of l^{th} decision-maker $(1 \leq l \leq e)$. Decision-makers make evaluations considering the scale given in Table 2 also.

Step 2. Construct the Aggregated IVAIF decision matrix. By using the IIFWA operator (3), the aggregated IVAIF decision matrix is generated as follows:

$$\widetilde{X} = \left[\widetilde{x}_{ij}\right]_{n \times m} = \begin{bmatrix} \widetilde{x}_{11} & \cdots & \widetilde{x}_{1m} \\ \widetilde{x}_{21} & \cdots & \widetilde{x}_{2m} \\ \widetilde{x}_{n1} & \cdots & \widetilde{x}_{nm} \end{bmatrix} \tag{19}$$

where $\widetilde{x}_{ij}$ represent the aggregated elements of the matrix (11). The elements of the aggregate matrix (19) were obtained by applying expression (3).

Aggregated IVAIF weight vector is formed in the second step, as is seen above.

$$\widetilde{W} = \left[\widetilde{w}_j\right]_{1 \times m} = \begin{bmatrix} \widetilde{w}_1 \\ \vdots \\ \widetilde{w}_m \end{bmatrix} \tag{20}$$

where $\widetilde{w}_j$ represents the aggregated weighting, coefficients obtained by applying expression (3).

Step 3. Construct the weighted aggregated IVAIF decision matrix. In this step, the aggregated IVAIF matrix is weighted by multiplying the weights of criteria with the help of the Eq. (21).

$$\widetilde{r}_{ij} = \widetilde{x}_{ij} \otimes \widetilde{w}_j \tag{21}$$

Then, the weighted IVAIF matrix $\widetilde{W}$ is generated as follows:

$$\widetilde{R} = \left[\widetilde{r}_{ij}\right]_{n \times m} = \begin{bmatrix} \widetilde{r}_{11} & \ldots & \widetilde{r}_{1m} \\ \widetilde{r}_{21} & \ldots & \widetilde{r}_{2m} \\ \widetilde{r}_{n1} & \ldots & \widetilde{r}_{xn} \end{bmatrix} \tag{22}$$

Step 4. Compute the interval-valued intuitionistic fuzzy negative ideal solution. IVAF negative ideal solution is calculated with the help of Eq. (23).

$$\begin{aligned} \widehat{ns} &= \left[\widehat{ns}_j\right]_{1 \times m}; \widehat{ns}_j = \min_i \widetilde{r}_{ij} \\ &= \left[\left(\min_i \widetilde{a}^r_{ij}, \min_i \widetilde{b}^r_{ij}, \max_i \widetilde{c}^r_{ij}, \max_i \widetilde{d}^r_{ij},\right)\right] \end{aligned} \tag{23}$$

Step 5. Compute Euclidean and Hamming distances of alternatives from negative-ideal solution. Using Eqs. (24) and (25), Euclidean and Hamming distances of alternatives from negative-ideal solutions are calculated. The distance measures between two IVIFSs are defined as follows: (Park et al. 2008; Roy et al. 2019; Özlem et al. 2021). Euclidean and hamming distances represent $dE\ (\widetilde{\alpha}_1, \widetilde{\alpha}_2)$ and $dH\ (\widetilde{\alpha}_1, \widetilde{\alpha}_2)$ for two sets of IVIFS $\widetilde{\alpha}_1 = [a_1, b_1], [c_1, d_1]$ and $\widetilde{\alpha}_2 = [a_2, b_2], [c_2, d_2]$ can be computed with Eqs. (16) and (17).

IVIFS Euclidean (dE) distances:

$$dE(\widetilde{\alpha}_1, \widetilde{\alpha}_2) = \sqrt{\frac{1}{4}(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2 + (d_1 - d_2)^2} \tag{24}$$

IVIFS Hamming (dH) distances:

$$\begin{aligned} dH(\widetilde{\alpha}_1, \widetilde{\alpha}_2) = &\frac{1}{4}|a_1 - a_2| + |b_1 - b_2| + |c_1 - c_2| \\ &+ |d_1 - d_2| \end{aligned} \tag{25}$$

Step 6. Determine the relative assessment matrix. The relative assessment matrix is determined in this step by using Eqs. (26) and (27).

$$RA = [p_{il}]_{n \times m} = \begin{bmatrix} p_{11} & \ldots & p_{1l} \\ p_{21} & \ldots & p_{2l} \\ p_{n1} & \ldots & p_{ln} \end{bmatrix} \tag{26}$$

$$p_{ik} = (dE_i - dE_l) + t(dE_i - dE_l)x(dH_i - dH_l), \tag{27}$$

where $l \in \{1, 2, \ldots, n\}$ and t is a threshold function which recognizes the equality of the Euclidean distances of two alternatives and is defined as (Yeni and Özçelik 2019):

$$t(x) = \begin{cases} 1\ if\ \theta \le |x| \\ 0\ if\ \theta > |x| \end{cases} \tag{28}$$

The decision-maker can set the threshold parameter (θ) of this function. Experts determine the θ value between 0.01 and 0.05 (Keshavarz Ghorabaee et al. 2016).

Step 7. Compute the assessment score (AS_i). In this step, the assessment score (AS_i) of each alternative is computed with the help of Eq. (29).

$$AS_i = \sum_{l=1}^{n} p_{il} \tag{29}$$

Considering the assessment score of each option, alternatives are ranked. The option that has the highest score is determined as the best alternative.

3 The numerical illustration

Here, we applied the Interval-Valued Atanassov Intuitionistic Fuzzy CODAS technique (IVAIF-CODAS) and examined the IVAIF-CODAS technique results. The basic algorithm of the proposed model can be seen in Fig. 1.

Stage 1.1. Definition of the main problem: In the first step of the preparation process, the main problem motivating to carry out this study for researchers has been determined. In addition to that, the research questions have also been determined in this process. The main problems are determined as follows:

- What are the essential criteria for selecting the appropriate route in international freight transportation?
- What are the primary route options between Turkey and European countries?
- Is there any mathematical model or methodological frame to solve these selection problems applied in road freight transportation? Or do decision-makers decide on selecting transport routes based on their own experiences, knowledge, and competencies without using any model?

Stage 1.2. Construction of the board of experts: To obtain more realistic and applicable results, a board of experts consists of five highly experienced professionals. All experts are company owners in road freight transportation, and three of them are the president of the professional association on transportation. Details of the experts are given in Table 3. Four members of the board of experts are the members of UTİKAD (Association of Producers of Transport and Logistics Services) and one member of UND (International Transporter Association).

Stage 1.3. Determination of the criteria and decision alternatives: In the third step of the preparation process,

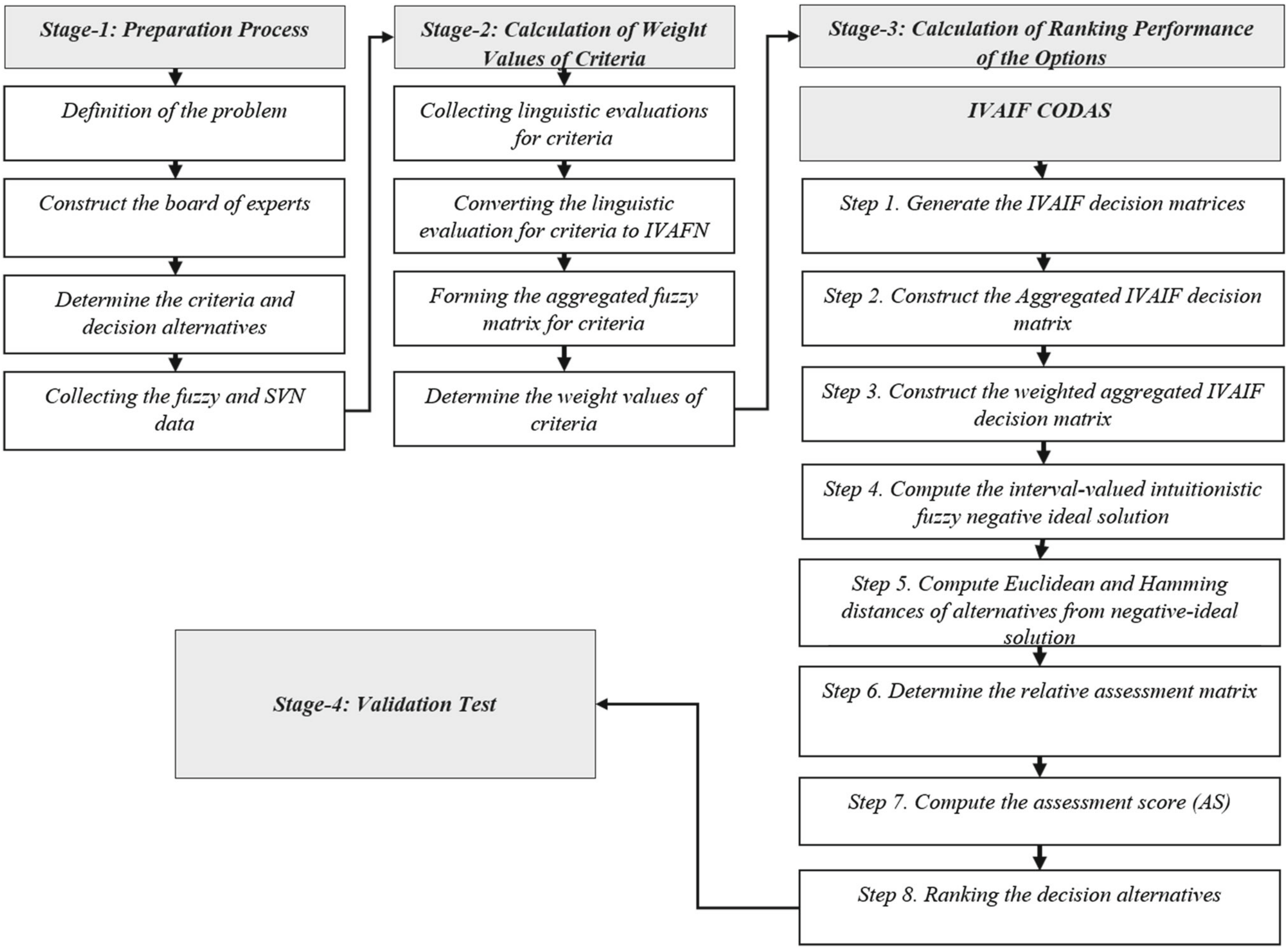


Fig. 1 The basic algorithm of the proposed model

Table 2 Details of the Members of the Board of Experts

	Institutions	Duty	Experience	Graduation	Title	Association
DM-1	Genel Transport Co	Chairman	28	Business	License	UTİKAD
DM-2	MT Transport Co	Chairman	32	Engineering	License	UTİKAD
DM-3	UTİKAD	Chairman	35	Engineering	License	UTİKAD
DM-4	KSN Logistics Co	Chairman	21	Engineering	M.A	UTİKAD
DM-5	Nalçacı Transport Co	Vice- Chairman	19	Economy	License	UND

Table 3 The decision alternatives for transport route selection between Turkey and Europe

Code	Route
Route-1	Bursa—Istanbul—Bulgaria—Romania (Free)—Hungary (Free)—Austria—Frankfurt/ Germany
Route-2	Bursa—Istanbul—Bulgaria—Serbia—Hungary (Free)—Austria—Frankfurt/ Germany
Route-3	Bursa—Istanbul—Bulgaria—Serbia—Szeged—Wels (Ro-La)—Austria—Frankfurt/ Germany
Route-4	Bursa—Istanbul—Bulgaria—Serbia—Croatia—Slovenia—Austria—Frankfurt/ Germany
Route-5	Bursa—İzmir—Çeşme-Trieste (Ro-Ro)—Austria—Frankfurt/ Germany
Route-6	Bursa—Istanbul—Pendik-Trieste (Ro-Ro)—Austria—Frankfurt/ Germany

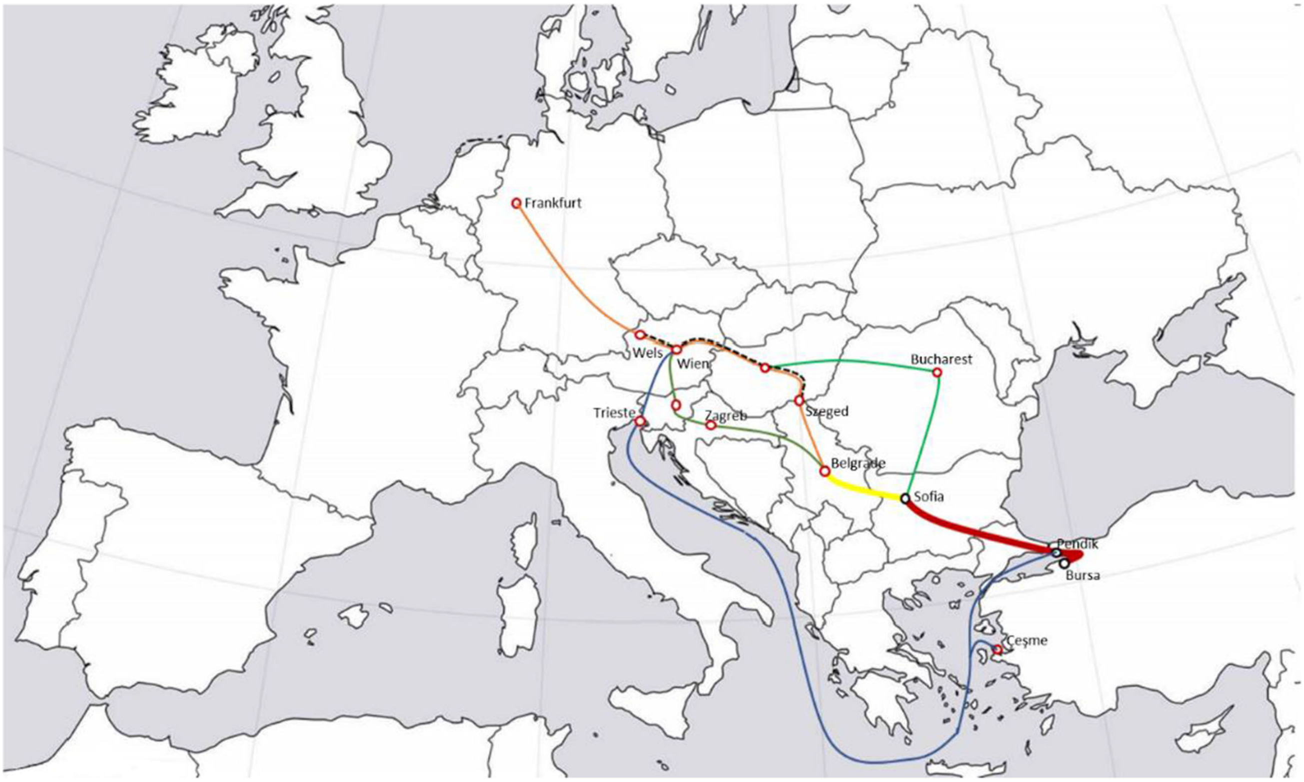


Fig. 2 Route alternatives between Turkey and Europe

Table 4 The decision alternatives for transport route selection between Turkey and Europe

Code	Criteria	DM-1	DM-2	DM-3	DM-4	DM-5	Geo Mean
C1	Transport Costs	7	8	8	9	7	7.765
C2	Transport Speed	7	6	8	7	7	6.971
C3	Security and Safety	6	7	7	5	7	6.346
C4	Environmental Awareness	8	7	5	5	6	6.093
C5	Legal Limitations	7	5	9	5	8	6.608
C6	Receiving Logistic Service	6	5	4	7	8	5.827
C7	Distance	5	4	6	5	7	5.305
C8	Accessibility	2	3	3	4	2	2.702
C9	Reliability	3	2	2	4	2	2.491
C10	Environmental friendliness	1	3	2	4	2	2.169
C11	Flexibility	3	4	1	1	2	1.888

Table 5 The selection criteria

Code	Criteria	Definition
C1	Transport Costs	The expenses involved in moving products or assets to a different place are often passed on to consumers
C2	Transport Speed	The rapidity of movement of any particular commodity by any combinations of transport modes
C3	Security and Safety	It refers to reduce risks existing in any international transport route
C4	Environmental Awareness	Reducing environmental impacts of transport modes used in a transport route
C5	Legal Limitations	Implementing regulations and legislations by departure, arrival, and transit countries
C6	Receiving Logistic Service	Providing logistics service for transport companies by service providers and
C7	Distance	Distance between starting and endpoints on the route in terms of kilometers

Table 6 Linguistic terms for criteria and rating the candidates with IVIFNs (Yeni and Özçelik 2019)

Linguistic terms	Symbol	IVIFNs			
(a) Linguistic scale for criteria evaluation					
Very Important	VI	0.900	0.900	0.100	0.100
Important	I	0.400	0.763	0.000	0.212
Medium	M	0.150	0.513	0.250	0.463
Unimportant	UI	0.000	0.363	0.400	0.613
Very Unimportant	VUI	0.100	0.100	0.900	0.900
(b) Linguistic scale for evaluation of the alternatives					
Linguistic terms	Symbol	IVIFNs			
Extremely Good	EG	1.0000	1.0000	0.0000	0.0000
Very Very Good	VVG	0.9000	0.9000	0.1000	0.1000
Very Good	VG	0.7333	0.8250	0.0000	0.1250
Good	G	0.6333	0.7250	0.1000	0.2250
Medium Good	MG	0.5333	0.6250	0.2000	0.3250
Fair	F	0.4333	0.5250	0.3000	0.4250
Medium Bad	MB	0.3333	0.4250	0.4000	0.4250
Bad	B	0.1500	0.2875	0.4500	0.6375
Very Bad	VB	0.0000	0.1375	0.6000	0.7875
Very Very Bad	VVB	0.1000	0.1000	0.9000	0.9000

researchers performed face-to-face interviews with each expert to ask the research questions and get their opinions on this issue. Firstly, decision-makers informed no mathematical model or methodological frame to determine the best route alternative in an assessment process. Also, they said that, including themselves, decision-makers responsible for deciding the route selection primarily consider the cost factors.

Then, preparing a list for criteria and decision alternatives was requested from decision-makers by the researchers. After the lists were collected, repetitive criteria and options were removed by researchers, and the final decision alternatives and criteria were determined by providing complete consensus among decision-makers. Options and criteria determined in the current paper are given in Tables 4 and 5.

First, researchers requested decision-makers (DMs) to prepare a list for the selection criteria; then, researchers collected these lists prepared given in Table 4 by decision-makers and prepared an aggregated list by eliminating the repetitive criteria. Finally, decision-makers gave a score between 1 and 9 to the selection criteria to identify the criteria's relative significance. Some criteria taking relative importance score under 5 were eliminated by providing complete consensus among decision-makers. The final list for the selection criteria and definitions is presented in Table 5.

According to the experts' opinions, the routes' starting point is determined as Bursa since the high volume of textile and garment products are exported from this city to European countries (Fig. 2).

Stage 1.4. Collecting the IVAIF data: In the last step of the preparation process, researchers directed questionnaires on the selection criteria and decision options to determine the linguistic evaluations for both the criteria and options. Decision-makers performed a linguistic evaluation considering the linguistic terms given in Table 6.

After the preparation process was completed, it was progressed to the next stage of the model, which involves applying the IVAIF CODAS methodology (*Stage 3)* for route evaluation.

Step 1. Firstly, decision-makers performed linguistic evaluations of both criteria and alternatives by considering the evaluation scale given in Table 2. Next, the collected linguistic evaluations were converted to the interval-valued Atanassov intuitionistic numbers by researchers, and IVAIF decision matrices were generated.

To apply the proposed IVIFN-CODAS multi-criteria model for evaluating routes $A_i(i = 1, 2, \ldots, 6)$ in international freight transportation, the experts $e(l = 1, 2, \ldots, 5)$

Table 7 Expert evaluation of the alternatives $A_i (i = 1, 2, \ldots, 6)$

Alternatives	Experts	C1	C2	C3	C4	C5	C6	C7
A1	DM-1	EG	MB	EG	MG	F	EG	MB
	DM-2	VVG	B	VVG	F	MB	VVG	B
	DM-3	VG	VB	VG	MB	B	VG	VB
	DM-4	EG	MB	EG	MG	F	EG	MB
	DM-5	VVG	B	EG	MG	MB	EG	MB
A2	DM-1	EG	B	EG	G	F	VG	F
	DM-2	VVG	VB	VVG	MG	MB	G	MB
	DM-3	VG	VVB	VG	F	B	MG	B
	DM-4	EG	B	EG	G	F	VG	F
	DM-5	VVG	B	VVG	MG	F	G	MB
A3	DM-1	VVG	MB	VG	VG	MG	G	MG
	DM-2	VG	B	G	G	F	MG	F
	DM-3	G	VB	MG	MG	MB	F	MB
	DM-4	VVG	MB	VG	VG	MG	G	MG
	DM-5	VG	B	G	G	F	G	F
A4	DM-1	EG	B	VVG	G	F	VG	F
	DM-2	VVG	VB	VG	MG	MB	G	MB
	DM-3	VG	VVB	G	F	B	MG	B
	DM-4	EG	B	VVG	G	F	VG	F
	DM-5	VVG	B	VVG	MG	F	VG	MB
A5	DM-1	EG	VVG	MB	EG	EG	F	VVG
	DM-2	VVG	VG	B	VVG	VVG	MB	VG
	DM-3	VG	G	VB	VG	VG	B	G
	DM-4	EG	VVG	MB	EG	EG	F	VVG
	DM-5	EG	VVG	MB	EG	EG	F	VG
A6	DM-1	EG	EG	B	EG	VG	G	EG
	DM-2	VVG	VVG	VB	VVG	G	MG	VVG
	DM-3	VG	VG	VVB	VG	MG	F	VG
	DM-4	EG	EG	B	EG	VG	G	EG
	DM-5	VVG	EG	B	VVG	VG	MG	EG

Table 8 Expert evaluation of the criteria C_j

Experts	C1	C2	C3	C4	C5	C6	C7
DM-1	VI	M	UI	UI	UI	UI	VUI
DM-2	VI	I	M	M	M	M	UI
DM-3	VI	UI	VUI	VUI	VUI	VUI	VUI
DM-4	I	UI	VUI	VUI	VUI	VUI	VUI
DM-5	VI	VI	I	I	I	I	M

evaluated the alternatives using a scale from Table 2. Expert evaluations of the alternatives are shown in Table 7.

After evaluating alternatives, the experts evaluated the criteria C_j $(j = 1, 2, \ldots, 7)$ to define the weight coefficients of the criteria. Expert evaluations of the criteria are shown in Table 8.

Step 2. In this step, expert evaluations of alternatives (Table 7) and criteria (Table 8) were aggregated by the IIFWA operator (6). Expert weighting coefficients $w_{DM1} = 0.26$, $w_{DM2} = 0.22$, $w_{DM3} = 0.19$, $w_{DM4} = 0.19$ and $w_{DM5} = 0.15$ were used to calculate the aggregate

Table 9 Aggregated initial decision matrix

Alt	A1	A2	A3	A4	A5	A6
C1	([1.000,1.000],[0.000,0.000])	([1.000,1.000],[0.000,0.000])	([0.820,0.854],[0.000,0.124])	([1.000,1.000],[0.000,0.000])	([1.000,1.000],[0.000,0.000])	([1.000,1.000],[0.000,0.000])
C2	([0.215,0.331],[0.447,0.550])	([0.111,0.226],[0.543,0.710])	([0.215,0.331],[0.447,0.550])	([0.111,0.226],[0.543,0.710])	([0.845,0.866],[0.000,0.120])	([1.000,1.000],[0.000,0.000])
C3	([1.000,1.000],[0.000,0.000])	([1.000,1.000],[0.000,0.000])	([0.671,0.765],[0.000,0.182])	([0.845,0.866],[0.000,0.120])	([0.243,0.353],[0.439,0.518])	([0.111,0.226],[0.543,0.710])
C4	([0.483,0.576],[0.245,0.359])	([0.569,0.662],[0.156,0.287])	([0.671,0.765],[0.000,0.182])	([0.569,0.662],[0.156,0.287])	([1.000,1.000],[0.000,0.000])	([1.000,1.000],[0.000,0.000])
C5	([0.354,0.453],[0.356,0.455])	([0.369,0.469],[0.341,0.455])	([0.467,0.560],[0.261,0.373])	([0.369,0.469],[0.341,0.455])	([1.000,1.000],[0.000,0.000])	([0.686,0.780],[0.000,0.167])
C6	([1.000,1.000],[0.000,0.000])	([0.671,0.765],[0.000,0.182])	([0.584,0.678],[0.140,0.271])	([0.686,0.780],[0.000,0.167])	([0.369,0.469],[0.341,0.455])	([0.569,0.662],[0.156,0.287])
C7	([0.243,0.353],[0.439,0.518])	([0.354,0.453],[0.356,0.455])	([0.467,0.560],[0.261,0.373])	([0.354,0.453],[0.356,0.455])	([0.820,0.854],[0.000,0.124])	([1.000,1.000],[0.000,0.000])

Table 10 IVIFNs weighted matrix

Alt	A1	A2	A3	A4	A5	A6
C1	([0.863,0.885],[0.000,0.113])	([0.863,0.885],[0.000,0.113])	([0.708,0.756],[0.000,0.223])	([0.863,0.885],[0.000,0.113])	([0.863,0.885],[0.000,0.113])	([0.863,0.885],[0.000,0.113])
C2	([0.085,0.212],[0.447,0.704])	([0.044,0.144],[0.543,0.809])	([0.085,0.212],[0.447,0.704])	([0.044,0.144],[0.543,0.809])	([0.332,0.554],[0.000,0.420])	([0.393,0.639],[0.000,0.342])
C3	([0.141,0.412],[0.000,0.565])	([0.141,0.412],[0.000,0.565])	([0.095,0.315],[0.000,0.645])	([0.119,0.357],[0.000,0.617])	([0.034,0.145],[0.439,0.791])	([0.016,0.093],[0.543,0.874])
C4	([0.068,0.237],[0.245,0.721])	([0.080,0.273],[0.156,0.690])	([0.095,0.315],[0.000,0.645])	([0.080,0.273],[0.156,0.690])	([0.141,0.412],[0.000,0.565])	([0.141,0.412],[0.000,0.565])
C5	([0.050,0.187],[0.356,0.763])	([0.052,0.193],[0.341,0.763])	([0.066,0.231],[0.261,0.728])	([0.052,0.193],[0.341,0.763])	([0.141,0.412],[0.000,0.565])	([0.097,0.321],[0.000,0.638])
C6	([0.141,0.412],[0.000,0.565])	([0.095,0.315],[0.000,0.645])	([0.083,0.279],[0.140,0.683])	([0.097,0.321],[0.000,0.638])	([0.052,0.193],[0.341,0.763])	([0.080,0.273],[0.156,0.690])
C7	([0.021,0.085],[0.787,0.878])	([0.031,0.109],[0.756,0.862])	([0.041,0.134],[0.720,0.842])	([0.031,0.109],[0.756,0.862])	([0.072,0.205],[0.621,0.779])	([0.088,0.240],[0.621,0.748])

Table 11 Ranking of the alternatives

Alternatives	AS_i	Rank
Route-1	-0.9777	3
Route-2	-1.3131	5
Route-3	-1.2931	4
Route-4	-1.5289	6
Route-5	2.2926	2
Route-6	2.8203	1

values of the alternatives using the IIFWA operator (6). The aggregated initial decision matrix $\widetilde{X} = \left[\widetilde{x}_{ij}\right]_{7\times 6}$ (Table 9) was obtained by aggregating the expert preferences from Table 7.

The elements at position A1-C1 from Table 9 are obtained by applying expression (6) as follows:

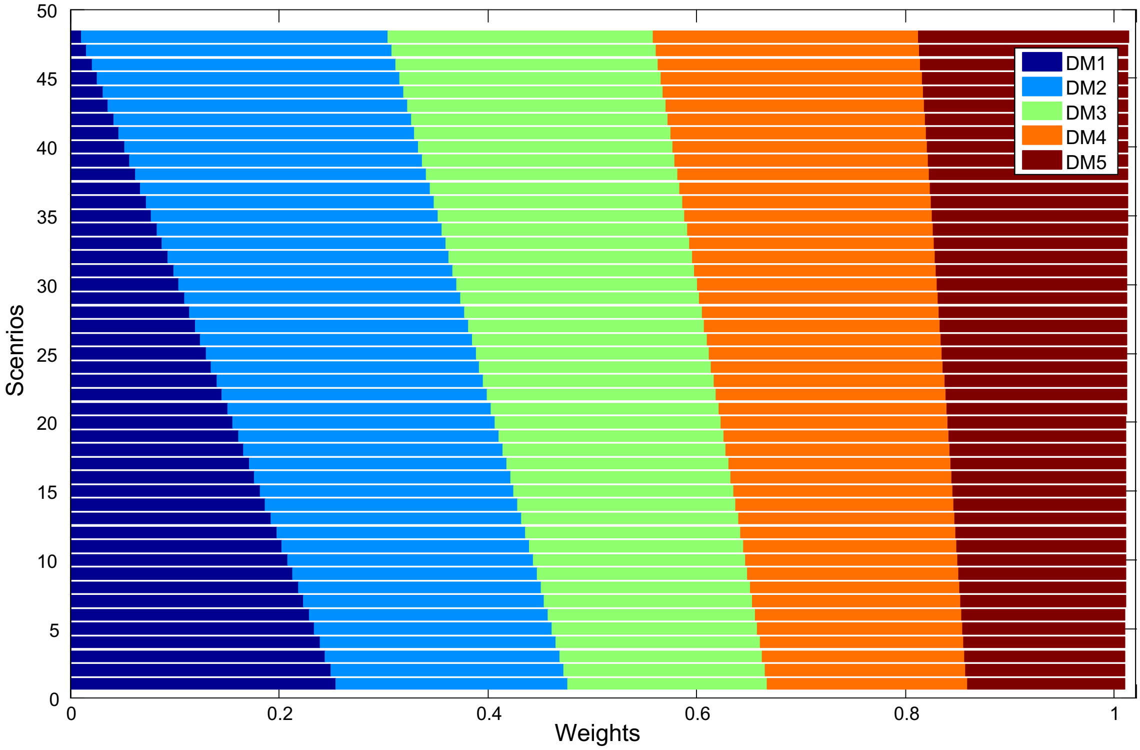


Fig. 3 New vectors of expert weight coefficients

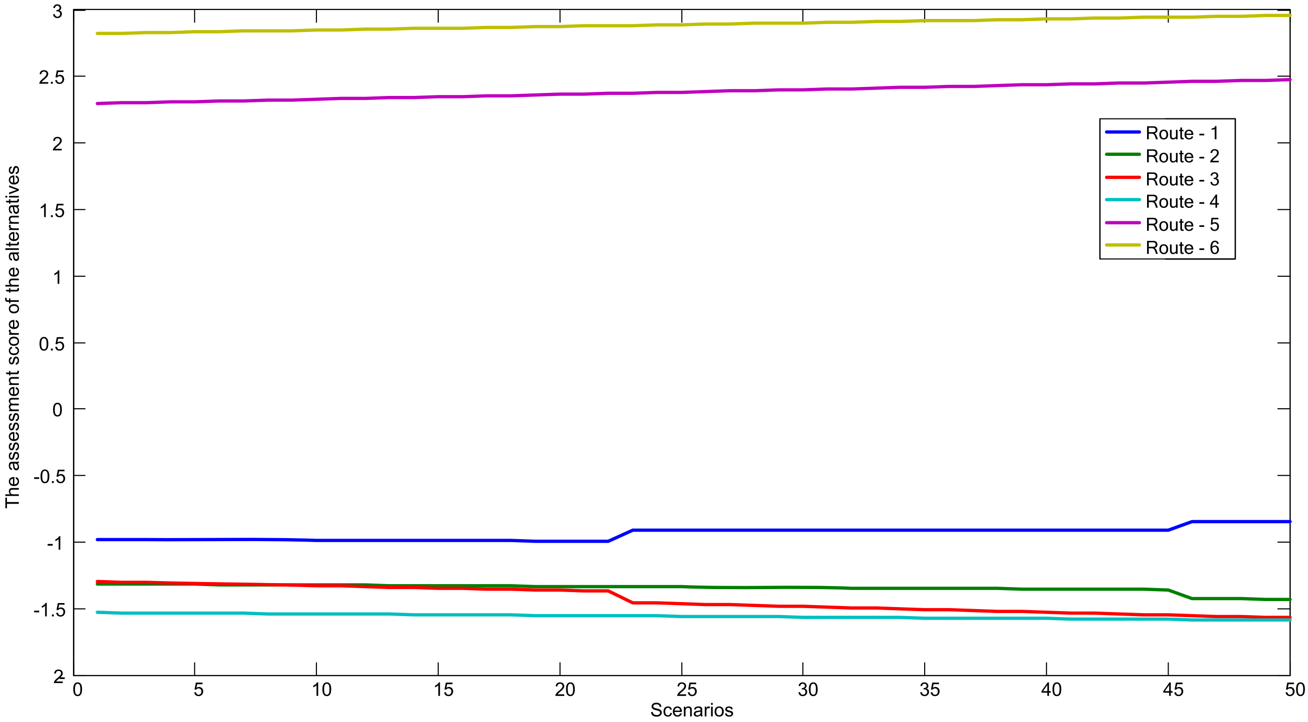
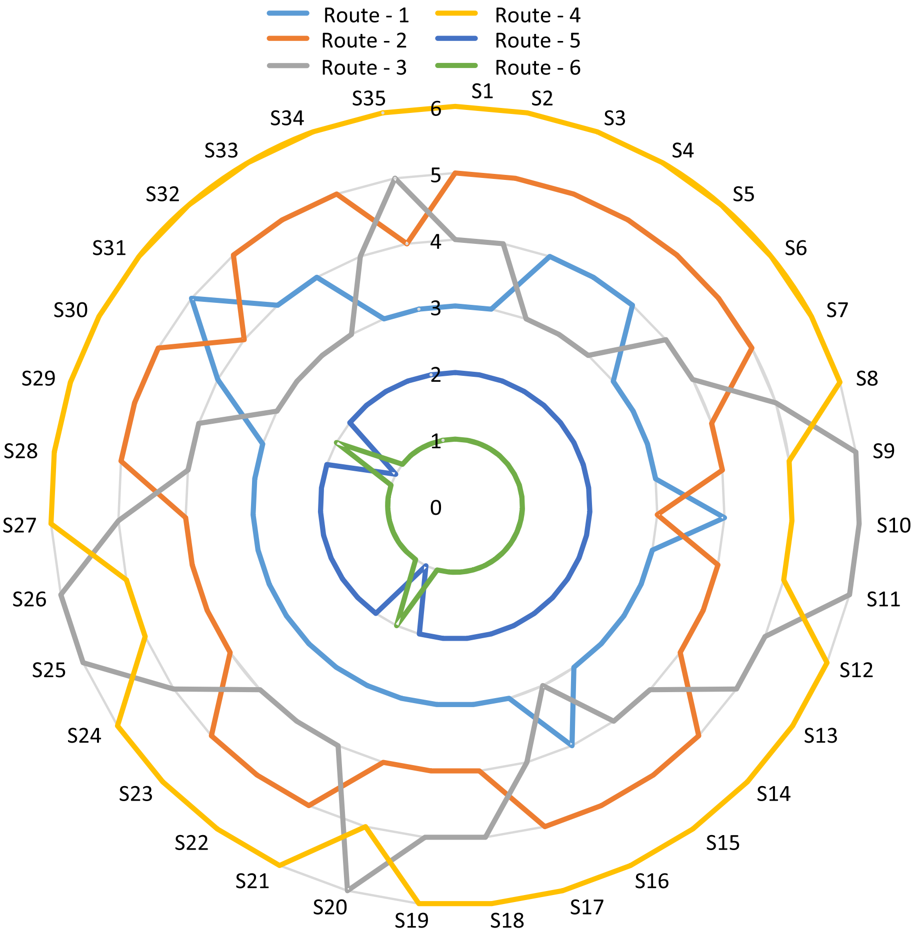


Fig. 4 The assessment score of the alternatives

Fig. 5 Rank alternatives through 35 scenarios



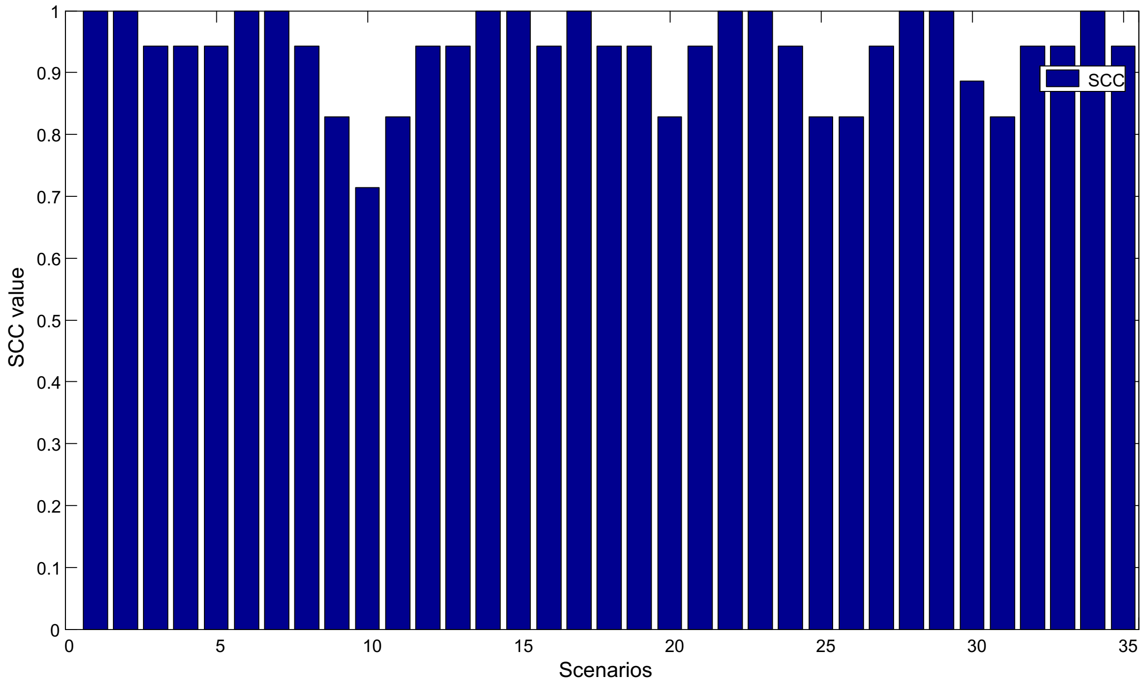


Fig. 6 SCC values through 35 scenarios

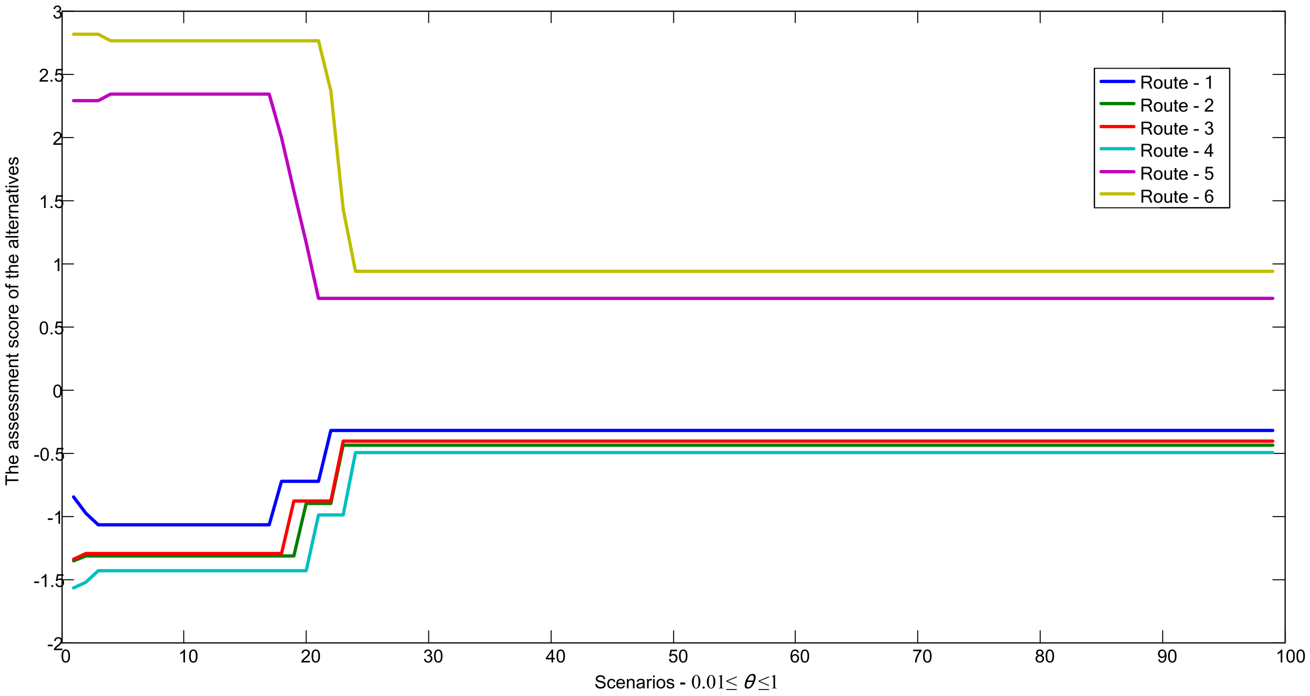


Fig. 7 Influence of parameter θ change on the assessment score of the alternatives

$$\widetilde{x}_{11}\{EG,VVG,VG,EG,VVG\}$$

$$= \left(\begin{bmatrix} 1-\left((1-1.0)^{0.26}\cdot(1-0.9)^{0.22}\cdot(1-0.73)^{0.19}\cdot(1-1.0)^{0.19}\cdot(1-0.9)^{0.15}\right), \\ 1-\left((1-1.0)^{0.26}\cdot(1-0.9)^{0.22}\cdot(1-0.825)^{0.19}\cdot(1-1.0)^{0.19}\cdot(1-0.9)^{0.15}\right) \end{bmatrix}, \\ \begin{bmatrix} 0.0^{0.26}\cdot0.10^{0.22}\cdot0.0^{0.19}\cdot0.0^{0.19}\cdot0.10^{0.15}, \\ 0.0^{0.26}\cdot0.10^{0.22}\cdot0.125^{0.19}\cdot0.0^{0.19}\cdot0.10^{0.15}, \end{bmatrix} \right)$$

$$=([1.000,1.000],[0.000,0.000])$$

Similarly, using expression (6), the aggregate values of the weight coefficients of the criteria were calculated:

$w_1 = ([0.863, 0.885], [0.000, 0.113]);$
$w_2 = ([0.393, 0.639], [0.000, 0.342]);$
$w_3 = ([0.141, 0.412], [0.000, 0.565]);$
$w_4 = ([0.141, 0.412], [0.000, 0.565]);$
$w_5 = ([0.141, 0.412], [0.000, 0.565]);$
$w_6 = ([0.141, 0.412], [0.000, 0.565]);$
$w_7 = ([0.088, 0.240], [0.621, 0.748]).$

Step 3. The IVIFNs weighted matrix $\widetilde{R} = \left[\widetilde{r}_{ij}\right]_{7\times6}$ is calculated by applying Eq. (11), Table 10.

Step 4. We obtain the IVIFN negative-ideal solution matrix $\widehat{ns} = \left[\widehat{ns}_j\right]_{1\times m}$ by applying Eq. (13). The IVIFN negative-ideal solution matrix is presented in the next section:

$\widehat{ns}_1 = ([0.708, 0.756], [0, 000, 0.223]);$
$\widehat{ns}_2 = ([0.044, 0.144], [0.543, 0.809]);$
$\widehat{ns}_3 = ([0.016, 0.093], [0.543, 0.874]);$
$\widehat{ns}_4 = ([0.068, 0.237], [0.245, 0.721]);$
$\widehat{ns}_5 = ([0.050, 0.187], [0.356, 0.763]);$
$\widehat{ns}_6 = ([0.052, 0.193], [0.341, 0.763]);$
$\widehat{ns}_7 = ([0.021, 0.085], [0.787, 0.878]).$

Step 5. After calculating the IVIFN negative-ideal solution matrix $\widehat{ns} = \left[\widehat{ns}_j\right]_{1\times m}$, we obtain the IVIFN dE and dH distances of alternatives from the IVIFN negative-ideal solution, using Eqs. (14) and (15).

a) By applying Eq. (14), we calculate IVIFN Euclidean (dE) distances. The following section presents the calculation of dE for alternative A1 and criterion C1:

$$dE(\widetilde{r}_{11}; \widehat{ns}_1) = \sqrt{\frac{\{0.8626 - 0.7075\}^2 + \{0.8848 - 0.7559\}^2 + \{0.000 - 0.000\}^2 + \{0.1127 - 0.2225\}^2}{4}} = 0.0574$$

In the same way, *dE* is calculated for alternative A1 and the remaining criteria. Summing *dE* for alternative A1 by all criteria, we obtain ED_1:

$$\begin{aligned} ED_1 &= 0.0574 + 0.0406 + 0.1780 + 0.0000 + 0.0000 \\ &\quad + 0.1149 + 0.0000 \\ &= 0.3909 \end{aligned}$$

In the same way, we calculate the Euclidean distances of the other alternatives $A_i(i = 1, 2, ..., 6)$:

$$ED_i = [0.3909, 0.3720, 0.3767, 0.3610,\ 0.5658, 0.6014]$$

b) By applying Eq. (15), we calculate IVIFN Hamming (*dH*) distances. The following section presents the *dH* calculation for alternative A1 and criterion C1:

$$dH(\widetilde{r}_{11}; \widehat{ns}_1) = \frac{|0.8626 - 0.7075| + |0.8848 - 0.7559| + |0.000 - 0.000| + |0.1127 - 0.2225|}{4} = 0.0985$$

The *dH* for alternative A1 and the remaining criteria are calculated in the same way. By summing *dH* by all criteria, we get EH_1:

$$\begin{aligned} EH_1 &= 0.0985 + 0.0772 + 0.3239 + 0.0000 + 0.0000 \\ &\quad + 0.2117 + 0.0000 \\ &= 0.7113 \end{aligned}$$

In the same way, we calculate the Hamming distances of the other alternatives $A_i(i = 1, 2, ..., 6)$:

$$EH_i = [0.7113, 0.6469, 0.6425, 0.6184, 1.0593, 1.1116]$$

Step 6. In order to obtain the elements of the relative assessment matrix $RA = [p_{il}]_{6\times6}$, we use previously obtained Euclidean (ED_i) distances and Hamming (HD_i) distances, Eq. (16).

$$RA = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{array} \begin{array}{c} \begin{array}{cccccc} A_1 & A_2 & A_3 & A_4 & A_5 & A_6 \end{array} \\ \begin{bmatrix} 0.0000 & 0.0189 & 0.0142 & 0.1228 & -0.5229 & -0.6108 \\ -0.0189 & 0.0000 & -0.0048 & 0.0110 & -0.6062 & -0.6942 \\ -0.0142 & 0.0048 & 0.0000 & 0.0158 & -0.6058 & -0.6937 \\ -0.1228 & -0.0110 & -0.0158 & 0.0000 & -0.6457 & -0.7336 \\ 0.5229 & 0.6062 & 0.6058 & 0.6457 & 0.0000 & -0.0879 \\ 0.6108 & 0.6942 & 0.6937 & 0.7336 & 0.0879 & 0.0000 \end{bmatrix} \end{array}$$

The element of the relative assessment matrix on the position *A2-A1* we obtain by applying Eq. (17): $p_{21} = (ED_2 - ED_1) + (0.02 \cdot (ED_2 - ED_1) \cdot (HD_2 - HD_1)) = (0.372 - 0.391) + (0.02 \cdot (0.372 - 0.391) \cdot (0.6469 - 0.7113)) = -0.0189$ The remaining elements of the relative assessment matrix are calculated in the same way.

Step 7. By applying Eq. (19), we calculate the assessment score (AS_i) for the first alternative A_1.

$$AS_1 = \sum_{k=1}^{6} p_{1k} = 0.0000 + 0.0189 + 0.0142 + 0.1228 - 0.5229 - 0.6108 = -0.9777.$$

In the same way, we calculate the assessment score of the other alternatives $A_i(i = 1, 2, ..., 6)$, as shown in Table 11.

Step 8. Based on the obtained values of the assessment score alternative, we can define the following initial rank of the route Route-6 > Route-5 > Route-1 > Route-3 > Route-2 > Route-4.

4 Validation test

Numerous studies in the literature (Paul et al. 2022; Donbosco and Ganesan 2022; Tutak and Brodny 2022) indicate the necessity of analyzing input parameters' influence on the initial ranking results. Subjectively defined parameters in the decision-making process can significantly affect the final results of the response (Riaz et al. 2022), so it is necessary to analyze their impact to validate the initial solution. In this study, the group of subjectively defined parameters includes: (1) weights of experts; (2) weighting coefficients of the criteria and (3) the threshold parameter (θ) used for calculations of the elements of the relative assessment matrix. In the next part of the paper, the influence of the mentioned parameters on the route selection's final results (alternative) is performed.

4.1 Influence of change of expert weight coefficients on ranking results

The initial results on the selection of the optimal route shown in Table 11 were obtained for the values of the experts' weight coefficients $w_{DM1} = 0.26$, $w_{DM2} = 0.22$, $w_{DM3} = 0.19$, $w_{DM4} = 0.19$ and $w_{DM5} = 0.15$. By applying the IIFWA operator (6), expert weights play an important role in aggregating expert preferences when evaluating alternatives and criteria. Therefore, in the following section, an analysis of the impact of the change in the experts' weight coefficients on the final choice of the transport route was performed.

In the following section, 50 new vectors of expert weight coefficients were created. The new vectors of weights of the experts (Fig. 3) were obtained by reducing the weight $w_{DM1} = 0.26$ by 2% in each scenario, while the values of the remaining weights were proportionally corrected to meet the condition that $\sum_{j=1}^{5} w_{DMj} = 1$.

After calculating the new weight vectors, a new assessment score of the alternatives was obtained for each vector (Fig. 4).

The results show that the experts' weights presented through 50 scenarios affect the change in the alternatives' assessment score. However, these changes in weighting factors do not lead to significant changes in the alternatives' ranks. Throughout all 50 scenarios, the ranks of the dominant alternatives, which include the first two by rank alternatives (Route-6 and Route-5), were confirmed. Also, the rank of the worst alternative (Route-4) did not change through the scenarios. There were minor changes in the rank of Route-2 and Route-3. For the weighting coefficient $0.218 \leq w_{DM1} \leq 0.255$, the initial ranking of alternatives was confirmed, while for the values of the weighting coefficient $0.003 \leq w_{DM1} \leq 0.213$, Route-2 and Route-3 switched their places. The presented analysis shows that the routes Route-5 (*Bursa—İzmir—Çeşme-Trieste (Ro-Ro)—Austria—Frankfurt / Germany*) and Route-6 (*Bursa—Istanbul—Pendik-Trieste (Ro-Ro)—Austria—Frankfurt / Germany*) represent dominant solutions and reasonable enough solutions regardless of the presented changes in the weights of experts.

4.2 Influence of change of criteria weight coefficients on ranking results

In the following part, the influence of the change of the weight coefficients of the criteria on the change of the alternatives' assessment score and the ranking results is analyzed. The influence of the change of the criteria weights performed through 35 scenarios was analyzed. For each criterion, five scenarios were formed. During the scenarios, the change of expert preferences according to the observed criterion was simulated. When simulating the change in expert preferences, the five-point scale values (Table 2) were used. In the first scenario, criterion C1 was assigned the value *VI* from the scale, while the original values were retained for the other criteria. In the following scenario, criterion C1 was assigned the value *I,* and in each subsequent scenario, the remaining values from the scale were assigned. During the first five scenarios, the change of weight coefficients of criterion C1 was simulated.

Similarly, in the following 30 scenarios, the change in the remaining criteria C2, C3, C4, C5, C6, and C7 was simulated. Thus, 35 new vectors of weight coefficients were obtained on which the analysis was based. After calculating the new weight vectors, the alternatives' assessment score was recalculated, so for each vector weight, a new ranking of alternatives was obtained (Fig. 5).

Figure 5 shows that the change in the weight coefficients of the criteria significantly affects the change in the value of the assessment score of the alternatives, affecting the changes in the ranks of alternatives. This experiment confirmed that the IVIFN CODAS model is sensitive to changes in the weights of the criteria. To determine the statistical significance of the obtained results through 35 scenarios with initial results, the Spearman rank correlation coefficient (SCC) was used. Using SCC, the ranks obtained through scenarios with the initial rank Route-6 > Route-5 > Route-1 > Route-3 > Route-2 > Route-4 were compared. Figure 6 shows the SCC values through 35 scenarios.

Based on the obtained values, it is noticed that the values of SCC through 34 scenarios are significantly above 0.8, which shows a highly significant correlation between the obtained ranks through scenarios and the initial rank. This is confirmed by the average value of SCC through scenarios, which is 0.879. Based on the literature (Bozanic et al. 2021; Kizielewicz et al. 2021) recommendations, all SCC values above 0.8 confirm the correlation between the considered ranks, based on which we can conclude that the initial rank is violated and valid. This fact is supported by the results shown in Fig. 5, which show that despite drastic changes in the values of the weighting coefficients of the criteria, there are no significant changes in the ranks of the dominant alternatives (Route-6 and Route-5). Minor changes in the ranks of the Route-6 and Route-5 alternatives occur in scenarios S21 and S29, in which the Route-6 and Route-5 alternatives swapped places. Based on this analysis, we can conclude that the routes Route-6 and Route-5 have a sufficient advantage over the remaining alternatives from the set and represent extremely dominant solutions from the considered set.

4.3 Influence of the change of the threshold parameter (θ) on the ranking results

In the following section, the change of the parameter θ on the change of the assessment score of the alternatives is analyzed. When calculating the initial rank of alternatives, based on the recommendations of Keshavarz Ghorabaee et al. (2016), the value $\theta = 0.02$ was adopted. To verify the IVIFN CODAS model results, the following part simulates the change in the value of the parameter θ in the interval $0.01 \leq \theta \leq 1$. In the first scenario, the value $\theta = 0.01$ was adopted, while in each subsequent scenario, the value of θ was increased by 0.01. Thus, a total of 100 scenarios were formed. The impact of the parameter change on the assessment score of the alternatives is shown in Fig. 7.

The values of the assessment score of the alternatives (ASi) obtained through the scenarios show that the parameter θ plays a significant role in defining the alternatives' final ranks. The results shown in Fig. 7 confirm such a conclusion. Despite significant changes in the ASi, the ranks of the alternatives did not change throughout the scenarios, i.e., through all 100 scenarios, the initial rank Route-6 > Route-5 > Route-1 > Route-3 > Route-2 > Route-4 was confirmed.

Based on the analysis presented in this section, we can conclude that the IVIFN CODAS model is a reliable tool for objective decision-making, which allows the processing of uncertain and incomplete group decisions. The IVIFN CODAS model's initial results were confirmed through all three experiments, thus confirming the robustness of the proposed multi-criteria framework. Also, the presented analysis confirmed the choice of routes Route-6 (*Bursa—Istanbul—Pendik-Trieste (Ro-Ro)—Austria—Frankfurt / Germany*) and Route-5 (*Bursa—İzmir—Çeşme-Trieste (Ro-Ro)—Austria—Frankfurt / Germany*) as optimal routes for international freight transportation, where Route-6 is a more favorable solution compared to Route-5.

5 Results and discussions

After the linguistic evaluations performed by decision-makers were transformed into the Interval-Valued Atanassov Intuitionistic Fuzzy numbers, the Interval-Valued Atanassov Intuitionistic Fuzzy CODAS technique was applied to evaluate the six alternative routes determined based on the evaluations made by experts. The obtained final results are presented in Table 9.

Evaluating alternative routes between Turkey and the EU countries has shown that international freight transport route 6, from Bursa city to Frankfurt, is the most preferred route option by international transport operators and logistics firms. Unlike others (except for route 5), carrying out multi-modal transport operations is the most crucial feature of this international transport route. It is a combined transport system consisting of many modes such as road freight transport, Ro-Ro transportation system, and Ro-La transport systems.

Negative environmental impacts of transport operations carried out on this route are comparatively lower than other alternatives since environment-friendly transportation modes such as maritime and railway transportation are used in large part of the route.

In addition, transport costs are lower because maritime and railway transport alternatives provide cheaper freightage; international operators and policymakers on international transportation incentivize multi-modal transportation by applying discounts on freightage of these kinds of transport modes. In addition to route 6, route 5 is the multi-modal transport route; it is ranked the second-best alternative in competitiveness. Route 4 is determined as the alternative, which is the least preferable and lowest competitive option. According to the main findings of the current paper, multi-modal transport routes have a significant superiority compared to unimodal transport routes in terms of preferability.

As a result of the current paper, international transportation routes based on unimodal road freight transport alternatives have lost their significance compared to routes carried out with multi-modal transportation. Although transport costs are the most crucial factors, external cost factors such as emissions, noise, congestions, energy consumption, and so on have recently become important. It has been observed that the more these factors continue to gain importance, the more crucial multi-modal transport routes will become. Considering this fact, this paper can help design the building of productive and effective international transportation routes between Turkey and the EU countries. The current study results prove that making investments for constructing multi-modal transport routes instead of unimodal transport routes can be more rational and practical to build more efficient and productive transport systems.

In order to validate the results obtained by applying the proposed model, a comprehensive sensitivity analysis was performed; it has corroborated that the results of the proposed model are substantially accurate. Also, the sensitivity analysis results prove that the suggested model can be applied to solve these kinds of decision-making problems.

In the first stage of the sensitivity analysis, while the change slightly influenced evaluation scores of decision alternatives in DM weights, it did not cause a significant change in the ranking of the options. In addition, the ranking positions for the first two alternatives did not change for all scenarios. When the DM weights are changed, route 6 is the best option, route 5 has remained the second-best alternative for all scenarios. These results prove that the Interval-Valued Atanassov Intuitionistic Fuzzy CODAS technique is a practical tool for solving the route selection problems encountered in the field of international transportation.

In the second stage of the sensitivity analysis, a sensitivity analysis was also performed to validate the results obtained by applying the proposed model; and it has corroborated that the results of the proposed model are substantially accurate. Also, the sensitivity analysis results prove that the suggested model can be applied to solve these kinds of decision-making problems.

Besides these consistent results, the proposed MCDM frame provides a range of valuable contributions in some matters as follows:

- The proposed model suggested in this paper uses intuitional fuzzy sets to reduce the impacts of uncertainties. Hence, the proposed model can contribute to the literature by proposing a solution that is accurate, applicable, and appropriate for real life.
- The literature emphasizes that the classical fuzzy sets may be insufficient in some situations (i.e., lack of information, leading to vagueness and lack of precision), and implementation of intuitional fuzzy (IF) or the interval-valued intuitionistic fuzzy approaches may be more appropriate. These approaches can provide more realistic and applicable results (Büyüközkan et al., 2018). In this perspective, the proposed model can present relevant and accurate results since it uses interval-valued fuzzy numbers.
- Implementing IVAIF CODAS and the interval-valued Atanassov intuitionistic fuzzy operator is suggested for aggregating the individual evaluations of decision-makers in group decision-making processes. Hence, this operator can provide valuable contributions in providing a more objective consensus, aggregating the experts' evaluations, and integrating them into the solution process.
- Decision-makers are included in the evaluation processes by considering the weights determined for themselves. When the differences among decision-makers related to their experiences, knowledge, and abilities are considered, using the interval-valued techniques is an appropriate and desirable situation to modeling the decision-making problems encountered in real life (Pamucar et al., 2020).

6 Conclusion

Sustainable route selection in uncertain environments for international transportation and logistics industries is crucial for decision-makers responsible for selecting an appropriate route in international freight transport operations. Since there are many conflicting criteria, route selection can be accepted as a highly complex decision-making problem; and a valuable and applicable methodological frame is needed to solve these kinds of problems. In this paper, the IVAIF CODAS technique, which is an extended version of the traditional CODAS technique, is suggested for obtaining more rational, applicable, and accurate results and solving these kinds of uncertain and complicated selection problems. Because human reasoning capability is inherently inexact (Roy et al. 2019), linguistic evaluations have been used for criteria and decision alternatives in the current paper.

Also, IVAIF numbers have used interval values instead of fuzzy triangular numbers (TFNS). When the results of this study are evaluated, it has been observed that the proposed IVAIF CODAS technique is valuable and applicable; and it can be applied to solve these kinds of decision-making problems. Also, the results of sensitivity analysis validate this evaluation. This method will help construct a more feasible transport route for policymakers. In addition, it can provide a range of advantages for transport operators and logistics companies to carry out more productive, effective, and low-cost transport operations.

Even though this research provides beneficial and valuable implications, transportation and logistics environments are highly variable for almost all factors, including costs and environmental effects. They can change with each passing day. Hence, solving these kinds of decision-making problems is extremely difficult. Therefore, this paper presents a methodological frame for decision-makers who work in international freight transportation.

Although route selection is a vital issue for transportation and logistics industries, the obtained information on this issue as a result of fieldwork shows that no mathematical model or methodological frame is used to determine the best route alternative in transportation and logistics. Decision-makers, who are responsible for selecting a transport route, make decisions mostly based on their own individual judgements and experiences and definite factors such as transport costs, existence of transit documents, and restrictions applied by transit countries.

The main contribution of this paper to the researchers who work in this field is to suggest a model based on an interval-valued fuzzy set to solve the route selection problem in international freight transportation. Another valuable contribution is presenting an IVAIF CODAS method as a reliable and practical tool to solve decision-making problems in situations such as lack of information and uncertainties.

On the other hand, some limitations of this paper exist; and these limitations can be summarized as follows: i) the selection criteria such as "Transport Costs, Transport Speed, Security and Safety, Environmental Awareness, Legal Limitations, Receiving Logistic Service and Distance have been determined together with experts who are highly experienced professionals. Also, different criteria and decision options that will occur soon based on developments (i.e., technological, economic, operational, and so on) can be included in the scope of future studies. Hence, the scope of this study can be extended by adding new criteria, sub-criteria, and options. ii) it is required to make more case studies to construct a user-friendly decision support system by generalizing the obtained results.

For future scientific studies, the CODAS technique can be extended with the help of different operators such as the normalized weighted and normalized weighted geometric Bonferroni aggregate functions (Ecer and Pamucar 2020), Heronian mean (HM) operators (Yu and Wu 2012), hybrid weight Power Heronian operator (wphap,q) and hybrid weight geometric Power Heronian operator (WGPHA p,q) (Pamucar and Jankovic, 2020). In addition, it can be examined comparatively with different approaches based on different IVIF sets such as fuzzy CODAS-SORT, interval-valued intuitionistic trapezoidal fuzzy, picture fuzzy, and Pythagorean fuzzy sets.

Author contributions Each author has equal contribution to the current paper.

Funding The authors have not disclosed any funding.

Declarations

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors. Informed consent was obtained from all individual participants included in the study.

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