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A hybridized Pythagorean fuzzy AHP and WASPAS method for airline new route selection: case study of Turkish Airline

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Abstract

Purpose – This study aims to provide a practical and novel solution for the complex multi-criteria decision-making (MCDM) problem of airline route selection, which is characterized by conflicting criteria, alternative routes, and complex judgments.

Design/methodology/approach – This study proposes a hybrid MCDM approach using Interval-valued Pythagorean Fuzzy AHP and Interval-valued Pythagorean Fuzzy weighted aggregated sum product assessment (WASPAS) methods. Decision analysis is applied to select a new route between different alternatives through selection criteria. Pythagorean Fuzzy AHP is used for weighting criteria, and Pythagorean Fuzzy WASPAS is used for assessing alternatives. The pair-wise linguistic comparisons of selection criteria are transferred into Pythagorean fuzzy numbers (PFNs) to weigh each criterion's importance.

Findings – The pair-wise linguistic comparisons of selection criteria are transferred into PFNs to weigh each criterion's importance. The results of these comparisons show that the main criteria, cost (43% weight) and demand (33% weight), impact route selection decisions more than social/economic conditions (15% weight) and competitiveness (9% weight). Regarding the criteria, the five routes alternative were evaluated by the route development experts, and the best route was selected with Pythagorean Fuzzy WASPAS.

Practical implications – The proposed model is used for a route selection problem of Turkish Airlines, the airline that flies to the most countries in the world.

Originality/value – To the best of the authors' knowledge, this study is the first to use the Interval-valued Pythagorean Fuzzy AHP combined with Interval-valued Pythagorean Fuzzy WASPAS to solve the route selection problem. This hybrid MCDM methodology presents a novel and feasible solution for selecting the new route for airlines.

Keywords Airline new route selection, Interval-valued Pythagorean fuzzy analytic hierarchy process, Interval-valued Pythagorean fuzzy WASPAS

Paper type Research paper

1. Introduction

In conjunction with economic growth, the global aviation industry plays a crucial role in passenger and freight transportation. Aside from creating an economic revival, the aviation industry empowers other industries such as e-commerce, hospitality, airports and many others. Therefore, decision-makers always search for better ways to improve aviation performance through global innovations and technological developments (Belobaba *et al.*, 2016).

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Due to technological advances in the airline industry, the total global passenger traffic has been increasing over the years, and this trend is expected to continue. Even under relatively conservative assumptions for economic growth over 10–15 years, an annual increase of 4–5% in global air transport will result in a doubling of total air transport over the same period (Gittens *et al.*, 2019). In 2019, the total traffic passenger demand increased by 3.6% compared to 2018, and the number of scheduled passengers transported by the airline industry extended to over 4.5 billion (ICAO, 2019).

Airlines require tools based on accurate methodologies due to the dynamic and high-cost nature of the aviation market. Factors such as the population, salary size, economic structure and historical or demographic characteristics of a region dictate market demand (Thekinen *et al.*, 2020). As the market size and demand for air travel grow, the number of destinations and airports rises. Thus, the need to balance demand-driven capacity increases as well. This capacity would be balanced with expanding the networks of existing airlines and entering new competitors into the global market. As a result, airlines always seek to apply the right strategies at the right time and place to stay profitable and functional in such a competitive environment. In short, flying to the correct destination would be one of the vital decision problems of an airline that needs to be answered accurately.

Regardless of their types and business models, airlines should make their decisions based on scientific and analytical decisions when it comes to investing in new routes. Otherwise, they may face deadly losses or the risk of missing out on an opportunity for a profitable investment. In other words, the decision to select a new route is one of the airlines' critical decisions that can decide the success or survival of the company. Under the constraints of fleet availability, route selection decisions determine where to offer services (Birolini *et al.*, 2021). Airline profitability and network availability are both affected by such decisions. However, they also impact the propagation of delays, the robustness of the network to service disruptions and the capacity of the network to handle traffic flow.

There is no public information on airline decision-making strategies. This has led to many researchers using a variety of methods to replicate these strategies. The main goal of this study is to present a guiding model for airlines willing to invest in opening new routes. The study proposes a model that evaluates the importance of factors affecting route selection while ranking alternative routes. The proposed model transfers the decision-makers and experts' experience into a measurable form. Due to the nature of the problem, the Multi-Criteria Decision Making (MCDM) methods were considered. The proposed model's novelty arises from the following:

- First, it applies a hybrid MCDM model, which combines the IV-PF AHP and IV-PF weighted aggregated sum product assessment (WASPAS) methods. The Pythagorean fuzzy numbers, which allow the decision-makers to state their choices without restriction and delimitation, are used to evaluate the selection criteria and rank the alternatives. To the authors knowledge, this study is the first one combining the named methods to solve the route selection problem;
- Second, the proposed model is used to solve the route selection problem of Turkish Airlines, the airline that flies to most countries in the world. The results show that the model can successfully solve a real problem; and
- Third, it will be a pioneering study that develops a novel evaluation model for the civil aviation industry. Thus, the model will guide experts and practitioners in the sector and provide valuable insights while implementing route expansion projects.

The structure of this paper consists of five sections. The research questions, objectives and the study's novelty were presented initially. The second part discusses the theoretical background of the airline's new route selection subject. This part summarized previous studies that used MCDM methods in the airline industry. Moreover, it discussed different methodologies used for route selection of airlines in the past. Based on discussed studies, a list of criteria for route selection is presented at the end of the section. Section 3 represents the proposed methodology of this study and its application in a full-service network airline in Turkey. The fundamentals of the fuzzy method are detailed, including the steps that were conducted for the IV-PF AHP and IV-PF WASPAS methods. Next, the application of this hybrid method is elaborated with the pairwise comparison of route selection criteria and evaluation of five alternative routes regarding the criteria. Section 4 discusses the findings of the applied hybrid methodology. The significance of the criteria and their effect on route selection are discussed. Moreover, the results present the best of the five alternative routes. The final section discusses the contributions, limitations and suggestions for future research.

2. Theoretical background

2.1 Airline route selection methodologies

Previous studies on the subject of airline route selection have used a wide variety of methodologies to address the issue. This section mentions some of these studies that conducted methodologies other than MCDM for route selection decision-making. Most of these studies used publicly available data on market demand, route distance and operating cost by using methods such as integer programming, linear programming and machine learning. Table 1 illustrates these studies and the methodologies that were used for them.

The early works on the route selection problem used linear programming (Dantzig, 1963; Kushige, 1963; Miller, 1967). Other methods, such as mixed integer programming (De Lamotte and Mathaisel, 1983) and Lagrangian-based algorithms (Balakrishnan *et al.*, 1990), were later introduced in the 1980s. Besides the conventional constant market share flight schedule, which uses integer or mixed-integer linear programs, Yan *et al.* (2007) improved a

Table 1. Summary table of the studies that used methodologies other than MCDM methods

Methodology	Studies
Linear programming	Dantzig, Kushige (1963)
Linear programming	Miller (1967)
Mixed integer programming	De Lamotte and Mathaisel (1983)
Lagrangian-Based algorithms	Balakrishnan *et al.* (1990)
Multi-Objective goal programing (MOGP)	Chang and Lee (2010)
A discrete event simulation model	Ye *et al.* (2012)
Investigating airline behavior	Evans and Schäfer (2014)
Utility function (linear programming)	Sha *et al.* (2015)
Discrete choice Random-Utility theory	Sha *et al.* (2016)
A Discrete-Event simulation model	Ye *et al.* (2016)
Multi-Objective programming	Chang *et al.* (2017)
Logit models	Nguyen and Nguyen (2018)
Panel probit model comparing Low-Cost and Full-Service airlines	Kong *et al.* (2019)
Comprising programming method with two objective functions	Chang *et al.* (2019)
Simulation of decision variables	Doyme *et al.* (2019)
Predictive model	Thekinen *et al.* (2020)
Mixed-integer Non-Convex optimization	Birolini *et al.* (2021)
Rules of destinations	İnce (2021)
Multilayer network theory	Gaggero and Piazza (2021)

Source: Authors' own creation

short-term scheduling model for Taiwan Airlines to enhance the efficiency of fleet routes and flight schedules.

Chang and Lee (2010) used multi-objective goal programing (MOGP) to determine and select an optimum central airport with its connecting airports. The MOGP model is used to design a point-to-point airline network. The study used data on routes between Taipei and Southeast Asia. Similarly, Chang *et al.* (2017) researched the flight routes between Taiwan and the USA to determine the most effective routes using multi-objective programming. This study is an example of a long-haul route selection model. Later, Chang *et al.* (2019) used a compromise programming model for selecting direct flight routes to find potential routes for airlines. The selection framework comprises maximizing total revenue and minimizing total cost with a case study analyzing destinations in the Taiwan–European region.

Sha *et al.* (2015) modeled the problem of route selection as a linear function of decision. A binary choice model was created from the linear function and used to model the decision of route selection. The choices for each variable in the linear function were forecasted using historical data sets. The suggested model provides an estimation of route addition and deletion. Later, Sha *et al.* (2016) used discrete choice random-utility theory to model the decision for adding or deleting a city-pair route. The study included methods for explaining the airline networks, defining selection sets and comparing and validating improved discrete choice models. In a similar study, Nguyen and Nguyen (2018) used logit models to study the relationship between binary variables in decision-making and multiple independent variables using data from the bureau of transportation statistics.

Ye *et al.* (2012) examined the analysis findings between airport-based costs and flight costs using the discrete event simulation model to select the best strategies for flight plans. Evans and Schäfer (2014) researched the airline route selection problem according to the congestion and delays that airlines face at airports. Later, Bojia *et al.* (2016) studied a discrete-event simulation model to evaluate the alternative route selection strategy. The model includes gathered departure/arrival airports, city-pair routes and other components for the industry. A combination of the Monte Carlo method and the optimal computing budget allocation simulation optimization technique is used to evaluate the performance of several strategies.

In more recent studies, Doyme *et al.* (2019) studied an iterative process to model the competition by using decision variables such as flight fares, frequency and aircraft type. They simulated these decision variables by keeping the network structure fixed. Kong *et al.* (2019) studied the route selection strategies of full-service and low-cost airlines. The panel-probit model examines the similarities and differences between these airlines. The research investigated how characteristics of the route, airline, rivals on the route and airport affect the decisions.

Thekinen *et al.* (2020) improved a presumable model of an airline route selection problem by using the Bureau of Transportation Statistics data. Birolini *et al.* (2021) studied the optimization of network planning, which consists of route selection, frequencies and the fleet type of an airline, with the help of an original mixed-integer non-convex optimization model. Ince (2021) researched 617 airlines to examine if there were some rules between the routes of different airlines. Gaggero and Piazza (2021) studied the subject of route entry in the USA domestic market by applying multilayer network theory to the airline industry.

2.2 Multi-criteria decision-making application in airline industry

Aviation comes with many alternatives and opposing or incomparable criteria (Dožić, 2019). Therefore, a need for MCDM methods is inevitable. Dožić (2019) indicated that the usage of fuzzy logic is widespread in the literature of the airline industry because of the necessity of making decisions under uncertainty, incorporating the vagueness of human thinking while considering multi-criteria decision problems. Therefore, there were many significant and successful fuzzy logic applications in different fields of the airline industry. This section focuses on the application of MCDM methods in the airline industry and mentions some of the studies that have been conducted in this regard.

Feng and Wang (2000) used the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to evaluate airlines' operational and financial performance using grey relation analysis. Tsaura *et al.* (2002) studied evaluating airline service quality with the help of the fuzzy set theory. For weighting the criteria, the Analytical Hierarchy Process (AHP) and for ranking the service quality of airlines, TOPSIS were used. Later, Gorener *et al.* (2017) used the interval type-2 Fuzzy Analytic Hierarchy Process (FAHP) and interval type-2 fuzzy technique for order preference by similarity to an ideal solution (FTOPSIS) to evaluate the supplier performance for airlines.

Liou and Chuang (2010) used an MCDM method to select outsourcing providers by using data from Taiwanese airlines. They suggested a hybrid MCDM model that consisted of the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method, the Analytical Network Process (ANP) and the VIKOR method. Relations between the criteria were created using DAMATEL. The weights of each criterion were determined with the help of ANP, and later, the alternatives were prioritized with the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method.

For problems involving aircraft selection, Sun *et al.* (2011) used MCDM based on robust decision-making criteria. Three MCDM methods were used to deal with aircraft selection problems, including Elimination and Choice Expressing Reality (ELECTRE), Simple Additive Weighting (SAW) and TOPSIS. Later, Su *et al.* (2018) studied the selection of landing paths for aircraft. A fuzzy selection strategy is suggested to deal with the problem by considering the fuzziness of environmental information and human judgment. The strategy was based on the idea of Fuzzy Multi-attribute Group Decision Making (FMAGDM).

Gomes *et al.* (2014) researched a Brazilian airline that wanted to invest in charter flights. They used the multi-criteria decision-aiding method of Novel Approach to Imprecise Assessment and Decision Environments to evaluate eight alternatives according to 11 criteria for the aircraft selection problem. Similarly, Dožić and Kalić (2014) used AHP to solve aircraft type selection problems for determining route networks and estimated air transport demand.

Zhang *et al.* (2015) evaluated airline service quality with a nonadditive fuzzy measure, which is more suitable than conventional additive measures. The study suggests the fuzzy measure and defines the Marichal entropy of the fuzzy measure to find a solution. Moreover, the aggregator Choquet integral concerning the fuzzy measure was presented. The model was verified by applying the comprehensive performance of the 15 airlines in the USA, using ten years of period data.

Table 2 summarizes the studies that used MCDM methods to solve various problems in the airline industry. Moreover, it illustrates studies objective, themes and used methods.

2.3 Multi-criteria decision-making applications of airline route selection problem

This section highlights some of the previous studies that conducted MCDM methods for airline route selection problems. It starts with one of the early works conducted by Janic and Reggiani (2002). In the study, researchers used the combination of three MCDM methods for an airline's new hub airport selection decision. The three MCDM methods were SAW, TOPSIS and AHP. These methods were applied to a preselected set of alternative airports.

Table 2. Summary table of studies that used MCDM methods in the airline industry

Studies	Objective	Themes	Methods used
Feng and Wang (2000)	Financial performance	Evaluation	TOPSIS, GRA
Tsaura *et al.* (2002)	Service quality	Evaluation	AHP, TOPSIS, fuzzy set theory
Liou and Chuang (2010)	Ground handlers	Selection	ANP, DEMATEL, VIKOR, SAW
Sun *et al.* (2011)	Aircraft	Selection	ELECTRE, SAW, TOPSIS
Dožić and Kalić (2014)	Aircraft	Selection	AHP
Gomes *et al.* (2014)	Aircraft	Selection	NAIDE, fuzzy sets
Zhang *et al.* (2015)	Service quality	Evaluation	Nonadditive MCA method, choquet integral
Görener *et al.* (2017)	Supplier performance	Evaluation	Interval type-2 FAHP, Interval type-2 FTOPSIS
Su *et al.* (2018)	Landing path	Selection	FMAGDM, TOPSIS-based simulation

Source: Authors’ own creation

Lu and Liu (2014) proposed an AHP framework for Taiwanese airlines. The determinants of potential service expansion were evaluated with a market opportunity analysis. The relative weights among these determinants were measured with a novel rank pairwise comparison and Grey Relational Analysis (GRA) to evaluate 12 airports in China. Likewise, Prasad and Raj (2017) and Yılmaz *et al.* (2018) have implemented the AHP method for determining the best destination and optimal route for different airlines. Moreover, Borkar *et al.* (2016) used multi-attribute decision-making (MADM) methodologies such as SAW, weighted product model (WPM), AHP and TOPSIS to select the optimal routes.

Perçin (2018) used a combined fuzzy decision-making approach to evaluate airline service quality in Turkey. His study identified 16 airline service quality criteria under five dimensions and applied a combined fuzzy approach, integrating the DEMATEL, ANP and VIKOR methods. This approach accounts for the interdependence of criteria, evaluates interactions and ranks airline service performance. The study also includes a sensitivity analysis to validate the robustness of its methodology.

Pineda *et al.* (2018) proposed an integrated model combining data mining and MCDM techniques to identify critical factors for enhancing airline performance. The model first uses a dominance-based rough set approach to extract essential factors, followed by the DEMATEL method combined with the Analytic Network Process (DANP) to build a comprehensive evaluation system. Finally, the VIKOR method is applied to select optimal improvement goals. The study finds that this model can function as a standard for assessing airline performance and enhancing operational efficiency to attain financial performance.

Rolka *et al.* (2020) presented a hybrid logical-arithmetic model for selecting flight routes. A hybrid MCDM model was conducted, including numerical and additional linguistic criteria. These criteria were converted into a crisp decision matrix to find the final ranking with the help of the TOPSIS method. Similarly, Deveci *et al.* (2017) used type-1 and type-2 fuzzy TOPSIS methods to evaluate potential routes for an airline in Turkey. They evaluated some destinations in the North American region according to the 11 criteria.

Zhang *et al.* (2018) studied China’s multi-airport system (MAS) and put forward an index system. An improved TOPSIS method was suggested to notice the coordinated development of regional airports. The Beijing capital airport air route was evaluated considering the development of the Beijing-Tianjin-Hebei regional MAS. Chen *et al.* (2014) combined FTOPSIS and multichoice goal programming (MCGP) to solve the location selection of logistic centers and find an appropriate logistic center by comparing alternative locations for the airline industry. In another study conducted in China, Loh *et al.* (2020) identified and ranked the airport selection criteria for low-cost carriers using a fuzzy analytical hierarchy process (FAHP).

Yu and Liu (2019) used fuzzy MCDM to solve the route selection problem by converting the linguistic language and choice information into trapezoidal fuzzy numbers with the given fuzzy language. The weight of each criterion in the route selection problem was determined using a programming model in which the total deviation between trapezoidal fuzzy numbers was minimized. In addition, Aydin and Seker (2020) researched a hub selection using the MCDM method to identify a new hub airport for Low-Cost Carriers. An interval-valued intuitionistic fuzzy set based on WASPAS and multi-objective optimization by ratio analysis (MULTIMOORA) methods were improved for the selection process.

Table 3 summarizes all studies and objectives that used the MCDM methods for airline route selection problems.

2.4 Selection criteria for evaluating a new route

Literature review reveals that there are many different criteria for the route selection of an airline. This study categorized these criteria into four main criteria: social/economic, cost, demand and competitiveness. Each main criterion consists of multiple sub-criteria. In total, there are twelve selected criteria. The main selection criteria are shown as C_i, where i is the number of relevant main criteria, and sub-criteria are shown as C_{ij}, where j is the number of the sub-criterion belonging to i^{th} main criterion. Table 4 illustrates all these criteria with their description. Moreover, Table 5 demonstrates the criteria that were considered for each study in the literature.

3. Methodology and application

This section discusses the details of the methodology, where IV-PF AHP and IV-PF WASPAS are integrated. Moreover, it provides the proposed model's application for a full-service airline in Turkey.

3.1 Research framework

In this study, Pythagorean fuzzy numbers (PFNs) are used in weighting evaluation criteria, as human thinking and judgments are imprecise, uncertain and ill-defined. The AHP defined in

Table 3. Previous studies that used MCDM methods in airline route selection

Studies	Objective	Methods used
Janic and Reggiani (2002)	Hub selection	SAW, TOPSIS, AHP
Lu and Liu (2014)	Route selection	AHP, market opportunity analysis, GRA
Chen *et al.* (2014)	Logistic center selection	FTOPSIS, MCGP
Borkar *et al.* (2016)	Route selection	SAW, WPM, AHP, TOPSIS
Prasad and Raj (2017)	Route selection	AHP
Deveci *et al.* (2017)	Route selection	Interval-1 Interval-2 FTOPSIS
Kucuk Yilmaz *et al.* (2018)	Route selection	AHP
Zhang *et al.* (2018)	Airport selection	TOPSIS
Yu and Liu (2019)	Route selection	Trapezoidal fuzzy numbers
Loh *et al.* (2020)	Airport selection	FAHP
Aydin and Seker (2020)	Hub selection	WASPAS, MULTIMOORA
Rolka *et al.* (2020)	Flight route selection	TOPSIS

Source: Authors' own creation

Table 4. Selected criteria and their descriptions

Criteria	Symbol	Description
Social/economic conditions	C_1	*This main criterion consists of the social and economic conditions of the destination region*
City population	C_{11}	This Sub-criterion is one of the social parameters for a new route. The catchment areas will give information about the estimated demand
Income (GDP) And trade	C_{12}	Income and GDP indicate the purchasing power of the destination city. It is also an economic measure that determines the growth of the county
Tourism potential	C_{13}	A high tourism potential for a destination point is an advantage for airlines. This Sub-criterion shows the destination attractiveness for passengers
Cost	C_2	*The total cost of the route includes expenses such as fuel, crew, airport charges, maintenance, handling and others*
Distance*Fuel	C_{21}	The distance of a route correlates with the cost of fuel consumption, which has the most significant share in an airline’s cost structure
Route cost	C_{22}	This Sub-criterion includes all costs for a route except fuel consumption. Costs such as airport charges, maintenance and staff expenses can significantly impact the destination route’s profitability
Demand	C_3	*This main criterion indicates the total passenger demand to/from the destination*
Number of economy class passengers	C_{31}	These passengers mostly fly for leisure purposes. An airline can obtain considerable revenue from this class of passengers with optimum revenue management
Number of business class passengers	C_{32}	This Sub-criterion indicates the number of business passengers. This type of passenger impacts the revenue of the route significantly
Number of connecting passengers	C_{33}	The number of passengers that flies from one point to another with a connecting flight
Cargo capacity	C_{34}	This criterion indicates the amount of cargo that flows from/to the destination in the route
Competitiveness	C_4	*This main criterion relates to the competitors that exist in the same route*
Price (fare)	C_{41}	This Sub-criterion indicates the average ticket fare of the route in which other competitors operate
Number of competitors	C_{42}	The number of airlines that operates flights in the route
Frequency of competitors	C_{43}	This Sub-criterion indicates the number of daily and weekly flights of other airlines which operates on the route

Source: Authors’ own creation

Table 5. List of MCDM studies and their criteria

Studies	Criteria used											
	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}	C_{34}	C_{41}	C_{42}	C_{43}
Gaggero and Piazza (2021)	√	√		√						√		
Birolini et al. (2021)	√	√		√		√	√			√		√
Aydin and Seker (2020)	√	√		√		√	√					
Thekinen et al. (2020)				√	√	√	√	√				
Loh et al. (2020)	√				√							
Chang et al. (2019)					√	√	√	√		√		√
Kong et al. (2019)			√	√		√	√	√			√	
Yu and Liu (2019)					√	√	√	√		√	√	√
Zhang et al. (2018)						√	√	√			√	
Kucuk Yilmaz et al. (2018)	√	√	√		√							
Deveci et al. (2017)	√	√	√	√	√	√	√	√			√	√
Chang et al. (2017)					√	√	√	√		√		√
Sha et al. (2016)				√	√	√	√	√				
Lu and Liu (2014)	√	√	√							√	√	√
Janic and Reggiani (2002)	√	√			√							

Source: Authors' own creation

PFNs is more relevant than the classical AHP. Subsequently, alternative airline routes are ranked using IV-PF WASPAS, which combines two MCDM approaches, the Weighted Sum Model (WSM) and WPM.

The fuzzy set theory was introduced by Zadeh (1965) to overcome the vagueness of human judgment. One of the main contributions of fuzzy set theory is having the capability of representing vague knowledge. It also lets mathematical operators and programming apply to the fuzzy domain. In situations where accurate information about a particular subject is lacking, we are forced to rely on an individual's judgment and ideas.

The fuzzy sets theory is a powerful tool for effectively considering the views of experts in such situations (Alrasheedi *et al.*, 2022; Tumsekcali *et al.*, 2021). The traditional AHP does not consider the uncertainty related to mapping one's judgment to a number. In addition, the subjective judgments of decision-makers or the preferences of decision-makers have a strong influence on the AHP, whereas fuzzy sets theory could deal with these deficiencies of AHP (Al-Barakati *et al.*, 2022; Mishra and Rani, 2021). Because of this advantage, an integration of AHP with the fuzzy set theory, known as fuzzy AHP (FAHP), is used with Pythagorean fuzzy numbers.

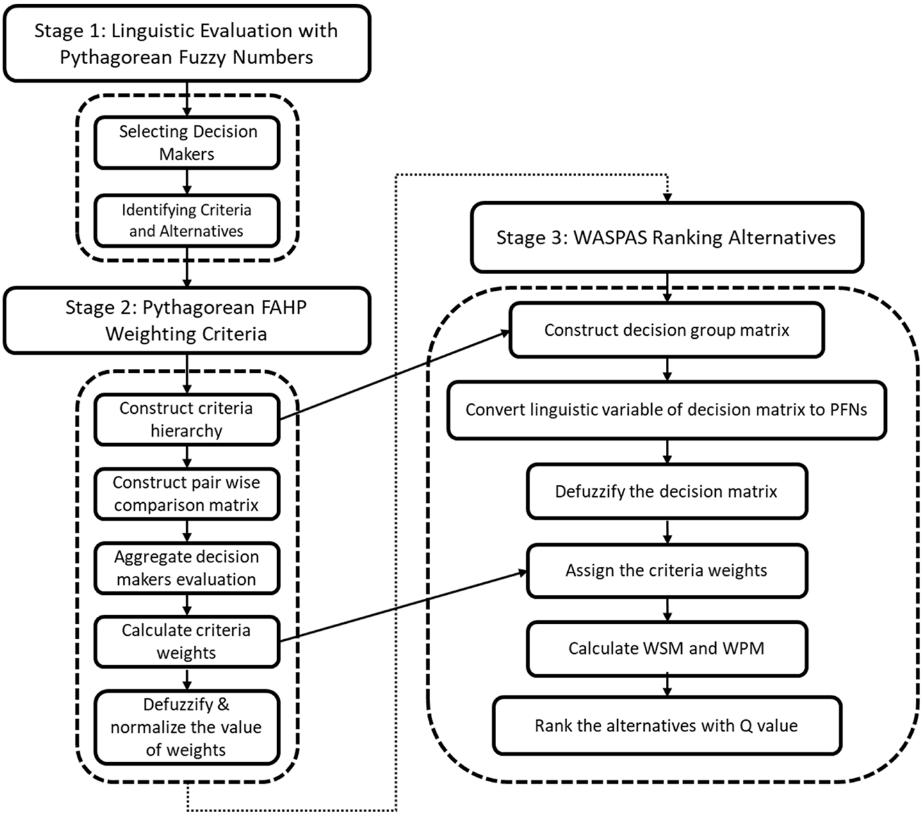
This study starts by identifying the problem. Next, with the help of experts or decision-makers, criteria and alternatives are evaluated to solve the problem. Later, IV-PF AHP is used to weigh the selection criteria, and IV-PF WASPAS is used to rank alternatives by evaluating the weighted criteria. The framework of this study is depicted in Figure 1.

3.2 Fuzzy sets

In this section, the preliminaries of Pythagorean Fuzzy Sets (PFSs) is introduced. Before that, the Intuitionistic Fuzzy Set (IFS) is summarized since the PFS is a generalization of IFS.

3.2.1 Intuitionistic fuzzy sets. **Definition 1**. Let a set X be a universe of discourse. An IFS *I* is expressed as follows:

$$I = \left\{ \langle x, I(\mu_I(x), v_I(x)) \rangle \ | x \in \mathrm{X} \right\},\ 0 \leq \mu_I(x) + v_I(x) \leq 1,\ \forall x \in \mathrm{X} \qquad (1)$$



Source: Authors' own creation

Figure 1. The framework of the proposed method

μ_I: $X \longrightarrow [0,1]$ defines the degree of membership of the element $x \in$ *to I*,
v_I: $X \longrightarrow [0,1]$ defines the degree of nonmembership of the element $x \in$ *to I*,
$\pi_I(x) = 1 - \mu_I(x) - v_I(x)$ is called the degree of indeterminacy of $x \in$ *to I*.

However, in some MCDM issues, the decision-makers' evaluation does not support equation (1). Namely, the sum of membership degrees and nonmembership degrees can be more than 1 in certain decision situations. This state cannot be expressed with the IFS. Thus, a novel model of PFS was proposed to cover this state and to prevent decision-makers from changing their preferences to fit within IFS's restraints (Zhang and Xu, 2014).

3.2.2 Pythagorean fuzzy sets. In PFS, the sum of the membership and nonmembership degree can exceed 1, but the sum of squares cannot.

Definition 2. Let a set, X, be a universe of discourse. A PFS *P* is expressed as follows:

$$P = \left\{\langle x, \mu_P(x), v_P(x)\rangle; x \in X\right\},\ 0 \leq (\mu_P(x))^2 + (v_P(x))^2 \leq 1,\ \forall x \in \mathrm{X} \tag{2}$$

Here, μ_P: X ⟶ [0, 1] describes the degree of membership of the element $x \in$ to P, ν_P: X ⟶ [0, 1] describes the degree of nonmembership of the element $x \in$ X to P and $\pi_P(x) = \sqrt{1-\mu_P(x))^2-(\nu_P(x))^2}$ is called the degree of indeterminacy of $x \in$ X, to P.

An Interval-Valued PFS (IV-PFS) is an extension of classical PFS, which relies on intervals rather than crisp numbers and, thus, reflects uncertainty better (Ayyildiz and Taskin Gumus, 2021). The detailed preliminaries can be found in Ayyildiz *et al.* (2021).

Definition 3. An IV-PFS P defined in X can be defined:

$$P = \left\{ \langle x, [\mu_{P_L}(x), \mu_{P_U}(x)], [\nu_{P_L}(x), \nu_{P_U}(x)] \rangle ; x \in X \right\}, \tag{3}$$

where $0 \le \mu_{P_L}(x), \mu_{P_U}(x), \nu_{P_L}(x), \nu_{P_U}(x) \le 1$, and ${\mu_{P_L}}^2(x) + {\nu_{P_L}}^2(x) \le 1$. Obviously, if $\mu_{P_L}(x) = \mu_{P_U}(x)$ and $\nu_{P_L}(x) = \nu_{P_U}(x)$, and IV-PFS becomes PFS. Furthermore, for convenience, $([\mu_{P_L}(x), \mu_{P_U}(x)], [\nu_{P_L}(x), \nu_{P_U}(x)])$ is usually written as $\left([\mu_{P_L}, \mu_{P_U}], [\nu_{P_L}, \nu_{P_U}]\right)$ (Luo *et al.*, 2023).

In a similar fashion to PFS, the hesitation interval of P in IV-PFS is given by equation (4):

$$\pi_P(x) = [\pi_{P_L}(x), \pi_{P_U}(x)] = \left[\sqrt{1-{\mu_{P_U}}^2(x)-{\nu_{P_U}}^2(x)}, \sqrt{1-{\mu_{P_L}}^2(x)-{\nu_{P_L}}^2(x)} \right]. \tag{4}$$

Basic operations on IV-PFSs are defined by the following operations. Let $P_1 = \left([\mu_{1_L}, \mu_{1_U}], [\nu_{1_L}, \nu_{1_U}]\right)$ and $P_2 = \left([\mu_{2_L}, \mu_{2_U}], [\nu_{2_L}, \nu_{2_U}]\right)$ be two IV-PFNs, then;

$$P_1 \oplus P_2 = \left(\left[\sqrt{{\mu_{1_L}}^2 + {\mu_{2_L}}^2 - {\mu_{1_L}}^2 {\mu_{2_L}}^2}, \sqrt{{\mu_{1_U}}^2 + {\mu_{2_U}}^2 - {\mu_{1_U}}^2 {\mu_{2_U}}^2} \right], [\nu_{1_L}\nu_{2_L}, \nu_{1_U}\nu_{2_U}] \right); \tag{5}$$

$$P_1 \otimes P_2 = \left([\mu_{1_L}\mu_{2_L}, \mu_{1_U}\mu_{2_U}], \left[\sqrt{{\nu_{1_L}}^2 + {\nu_{2_L}}^2 - {\nu_{1_L}}^2 {\nu_{2_L}}^2}, \sqrt{{\nu_{1_U}}^2 + {\nu_{2_U}}^2 - {\nu_{1_U}}^2 {\nu_{2_U}}^2} \right] \right); \tag{6}$$

$$\lambda P_1 = \left(\left[\sqrt{1 - (1 - {\mu_{1_L}}^2)^{\lambda}}, \sqrt{1 - (1 - {\mu_{1_U}}^2)^{\lambda}} \right], [{\nu_{1_L}}^{\lambda}, {\nu_{1_U}}^{\lambda}] \right), \ \lambda > 0; \tag{7}$$

$${P_1}^{\lambda} = \left([{\mu_{1_L}}^{\lambda}, {\mu_{1_U}}^{\lambda}], \left[\sqrt{1 - (1 - {\nu_{1_L}}^2)^{\lambda}}, \sqrt{1 - (1 - {\nu_{1_U}}^2)^{\lambda}} \right] \right), \ \lambda > 0; \tag{8}$$

Two compare two IV-PFNs, the values of score functions can be compared. The score function of an IV-PFN, $P_1 = \left([\mu_{1_L}, \mu_{1_U}], [\nu_{1_L}, \nu_{1_U}]\right)$, is defined as:

$$S(P_1) = \frac{({\mu_{1_L}}^2 + {\mu_{1_U}}^2 - {\nu_{1_L}}^2 - {\nu_{1_U}}^2)}{2}. \tag{9}$$

In certain cases, score functions of two IV-PFNs can be equal. To deal with such cases, an accuracy function can be defined (Garg, 2017) as:

$$H(P_1) = \frac{\left({\mu_{1_L}}^2 + {\mu_{1_U}}^2 + {\nu_{1_L}}^2 + {\nu_{1_U}}^2\right)}{2}. \tag{10}$$

Definition 4. Let P_1 and P_2 be two IV-PFNs. Then:

(1) If $S(P_1) < S(P_2)$, then $P_1 \prec P_1$.
(2) If $S(P_1) > S(P_2)$, then $P_1 \succ P_1$.
(3) If $S(P_1) = S(P_2)$, then $P_1 \sim P_1$.

In the last case, $S(P_1) = S(P_2)$, the comparison must be done based on the accuracy functions. Hence:

(1) If $H(P_1) < H(P_2)$, then $P_1 \prec P_1$.
(2) If $H(P_1) > H(P_2)$, then $P_1 \succ P_1$.
(3) If $H(P_1) = H(P_2)$, then $P_1 \sim P_1$.

Definition 5. Let $P_i = \left([\mu_{i_L}, \mu_{i_U}], [\nu_{i_L}, \nu_{i_U}]\right)$, $(i = 1, 2, \ldots, n)$ be a collection of n IV-PFNs and $w = (w_1, w_2, \ldots, w_{\mathrm{n}})$ be the weight vector of P_i. The weight vector has the following properties: $w_i \geq 0$ for $(i = 1, 2, \ldots, n)$, and $\sum_{i=1}^{n} w_i = 1$. Then, an Interval-valued Pythagorean Fuzzy Weighted Average (IVPFWA) operator is defined (Peng and Yang, 2016) as:

$$IVPFWA(P_1, P_2, \ldots, P_n) = \left(\left[\sum_{i=1}^{n} w_i \mu_{iL}, \sum_{i=1}^{n} w_i \mu_{iU}\right], \left[\sum_{i=1}^{n} w_i \nu_{iL}, \sum_{i=1}^{n} \nu_i \mu_{iU}\right]\right) \tag{11}$$

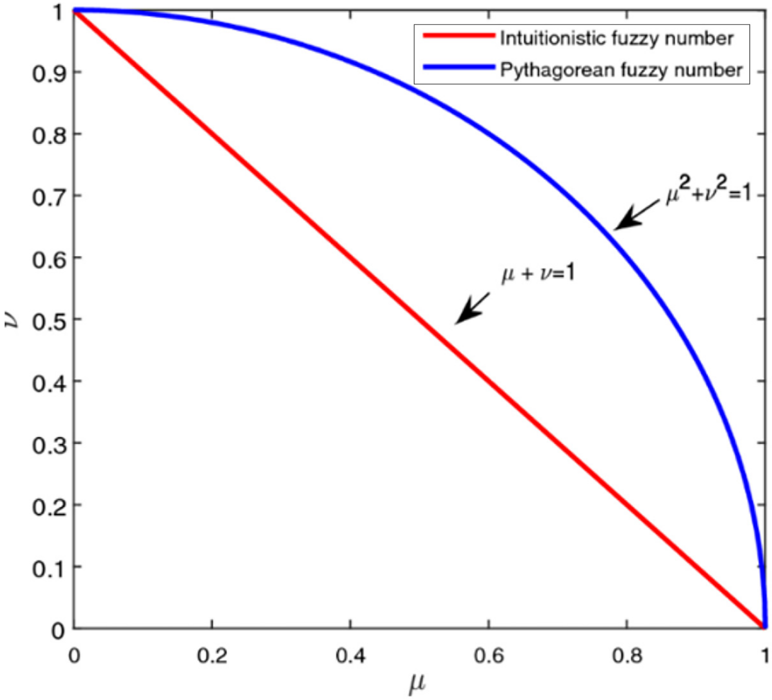
3.2.3 Promising properties of Pythagorean fuzzy numbers. As mentioned before, PFNs are a generalization of Intuitionistic Fuzzy Number (IFNs). They offer more flexibility in the manifestation of uncertainty. The advantages in presenting the degrees of membership degree and nonmembership hesitancy are essentially due to expanding the area for setting such value. In real life, the decision-maker's preferences may not be satisfied with the condition of IFSs that the sum of membership and nonmembership degrees should be less than or equal to 1. Conversely, in the PFS, the sum of the membership and nonmembership degrees can exceed 1. However, PFSs also sustain the advantages of membership (μ) and nonmembership (ν) functions.

The value range of the membership function and nonmembership function is expanded from a triangle to a quarter circle, as presented in Figure 2. This expansion of the value area makes the amount of information of PFSs extend 1.57 times that of the IFSs, and still, it ensures that IFSs are all PFSs (Fan *et al.*, 2022). In other words, the PFS maintains a larger preference area for decision-makers to express their opinions.

It can be concluded that in real-world situations where it is necessary to make a preference under uncertainty, PFSs have a higher potential to deal with incomplete and imperfect information when compared to IFSs. Simply put, they can be used to characterize the uncertainty more sufficiently and precisely. Therefore, this study used Interval-valued Pythagorean Fuzzy Numbers to deal with the vagueness of the decision-maker's opinions.

3.3 Interval-valued Pythagorean fuzzy analytical hierarchy process

After selecting the experts and identifying the selection criteria in the first stage of the proposed model, the next step is to determine the importance level of the criteria. In this section, based on the definitions described in the previous sections, the main steps of IV-PF AHP are shown.



Source: Akram *et al.*, 2019

Figure 2. The comparison of IFNs space and PFNs space

Step 1: The compromised pairwise comparison matrices of main criteria and sub-criteria in the form of $\boldsymbol{A} = (a_{jk})_{m \times m}$ are created regarding the linguistic evaluations of decision makers based on the scale in Table 6 proposed by Ilbahar *et al.* (2018). Here, m denotes the number of criteria. To aggregate the decision-makers preference matrices, the Interval-valued Pythagorean Weighted Geometric Aggregation (IVPWGA) operator in equation (11) is used.

Step 2: The difference matrices $\boldsymbol{D} = (d_{jk})mxm$ between the lower and upper values of the membership and nonmembership functions are determined using equations (12)–(13):

$$d_{jk_L} = \mu^2_{jkL} - v^2_{jkU} \tag{12}$$

$$d_{jk_U} = \mu^2_{jkU} - v^2_{jkL} \tag{13}$$

Step 3: The upper and lower interval multiplicative matrices $\boldsymbol{S} = (s_{jk})_{mxm}$ are defined as in equations (14)–(15):

$$S_{jk_L} = \sqrt{1000^{d_{jk_L}}} \tag{14}$$

Table 6. Linguistic scale for interval-valued Pythagorean FAHP

	PFN equivalents IVPF numbers			
Linguistic terms	Lower value of the membership degree, μ_L	Upper value of the membership degree, μ_U	Lower value of the nonmembership degree, v_L	Upper value of the nonmembership degree, v_U
Certainly low importance – CLI	0	0	0.9	1
Very low importance – VLI	0.1	0.2	0.8	0.9
Low importance – VI	0.2	0.35	0.65	0.8
Below average importance – BAI	0.35	0.45	0.55	0.65
Average importance – AI	0.45	0.55	0.45	0.55
Above average importance – AAI	0.55	0.65	0.35	0.45
High importance – HI	0.65	0.8	0.2	0.35
Very high importance – VHI	0.8	0.9	0.1	0.2
Certainly high importance – CHI	0.9	1	0	0
Exactly equal – EE	0.1965	0.1965	0.1965	0.1965

Source: (Ilbahar *et al.*, 2018)

$$S_{jk_U} = \sqrt{1000^{d_{jk_U}}} \tag{15}$$

Step 4: The indeterminacy value $\boldsymbol{\tau} = (\tau_{jk})_{mxm}$ is given by the following equation:

$$\tau_{jk} = 1 - \left(\mu^2_{jk_U} - \mu^2_{jk_L}\right) - \left(v^2_{jk_U} - v^2_{jk_L}\right) \tag{16}$$

Step 5: The indeterminacy values are multiplied with $\boldsymbol{S} = (s_{jk})_{mxm}$ matrix to get matrix of weights $\boldsymbol{T} = (t_{jk})_{mxm}$ before normalization. The matrix, $\boldsymbol{T} = (t_{jk})_{mxm}$, is formulated as in equation (17):

$$t_{jk} = \left(\frac{S_{jk_L} + S_{jk_U}}{2}\right)\tau_{jk} \tag{17}$$

Step 6: Each normalized priority weight w_j is calculated with equation (18):

$$w_j = \left(\frac{\sum_{k=1}^{m} t_{jk}}{\sum_{j=1}^{m}\sum_{k=1}^{m} t_{jk}}\right) \tag{18}$$

3.4 Interval-valued Pythagorean fuzzy weighted aggregated sum product assessment method

The last stage of the proposed methodology is evaluating alternatives according to the criteria using the IV-PF WASPAS method. This section introduces the steps of the Interval-valued Pythagorean Fuzzy WASPAS method using the linguistic scale of PFNs.

WASPAS method was developed by Zavadskas *et al.* (2012), who integrated two MCDM methods of WSM and WPM. The ranking of alternatives depends on the results of both WSM and WPM. WASPAS method is considered a compensatory method because of including two MCDM methods. Having independent criteria and transferring qualitative evaluation into quantitative assessments are other promising features of this method.

Before applying the method, it is necessary to perform a decision/evaluation matrix in the form of $\boldsymbol{X} = (x_{ij})_{nxm}$, where x_{ij} is the performance value of the ith alternative with respect to the jth criterion. Here, n is the number of alternatives, and m is the number of criteria. The decision matrix consists of linguistic evaluations of the experts, as given in Table 7. Then, linguistic variables are transformed into the corresponding Interval-Valued PFNs.

According to Chakraborty and Zavadskas (2014), the IV-PF WASPAS method's application steps can be summarized as follows:

Step 1 The normalized decision matrix: The evaluation matrix is normalized using equation (19) to make the values of the matrix comparable, where r_{ij} indicates the normalized value of the decision matrix of the ith alternative with respect to the jth criteria:

$$r_{ij} = \begin{cases} \dfrac{x_{ij}}{\max(x_{ij})}, \; if j \in C_b \\ \dfrac{\min(x_{ij})}{x_{ij}}, \; if j \in C_c \end{cases} \tag{19}$$

where c_b is the set of benefit criteria and C_c is the set of cost criteria.

Step 2 Weighted sum model (WSM): We apply equation (20) to calculate the additive relative importance value of each alternative, where w_j, $j = (1, 2, \ldots, m)$ indicates the weight of criteria and Q_{i}^{1} indicates the WSM value of the ith alternative:

$$Q_{\mathrm{i}}^{1} = \sum\nolimits_{j=1}^{m} w_j r_{ij} \tag{20}$$

Step 3 Weighted product model (WPM): equation (21) is used to calculate the multiplicative relative importance value of each alternative, where Q_{i}^{2} indicates the WPM value of the ith alternative:

$$Q_{\mathrm{i}}^{2} = \prod\nolimits_{j=1}^{m} (r_{ij})^{w_j} \tag{21}$$

Step 4 The joint generalized criterion: The joint generalized criterion value of each alternative, Q_i, is calculated with equation (22), where λ is a model parameter in WASPAS method. The value of λ is between 0 and 1. If $\lambda = 1$, the WASPAS method reduces to WSM, whereas it transforms into the WPM model when $\lambda = 1$:

Table 7. Linguistic terms for evaluating alternatives

Linguistic term	Abbreviation	Interval-valued Pythagorean fuzzy number
Extremely good	EG	([0.8,0.9], [0.1,0.2])
Very good	VG	([0.7,0.8], [0.2,0.3])
Good	G	([0.6,0.7], [0.3,0.4])
Fair	F	([0.5,0.6], [0.4,0.5])
Poor	P	([0.3,0.4], [0.6,0.7])
Very poor	VP	([0.2,0.3], [0.7,0.8])
Extremely poor	EP	([0.1,0.2], [0.8,0.9])

Source: Authors' own creation

$$Q_i = \lambda Q_i^1 + (1-\lambda) Q_i^2 \tag{22}$$

A common practice in the literature is to use $\lambda = 0.5$ (Ayyildiz and Taskin Gumus, 2020; Hatiboglu *et al.*, 2023).However, some studies propose to calculate the model parameter, λ, with equation (23) (Turskis *et al.*, 2015):

$$\lambda^* = \left(\frac{\sum_{i=1}^{n} Q_i^2}{\sum_{i=1}^{n} Q_i^1 + \sum_{i=1}^{n} Q_i^2} \right) \tag{23}$$

Step 5 The final Ranking of Alternatives: This step involves defuzzification of Q_i and ranking the crisp scores, Q_i^{cr}, in decreasing order. We use equation (24) for defuzzification process (Ayyildiz *et al.*, 2021):

$$Q_i^{cr} = \frac{\mu_L + \mu_L + \sqrt{1-v_L^2} + \sqrt{1-v_U^2} + \mu_L\mu_L - \sqrt{\sqrt{1-v_L^2}\sqrt{1-v_U^2}}}{4} \tag{24}$$

3.5 *Application of the proposed model to airline route selection problem*

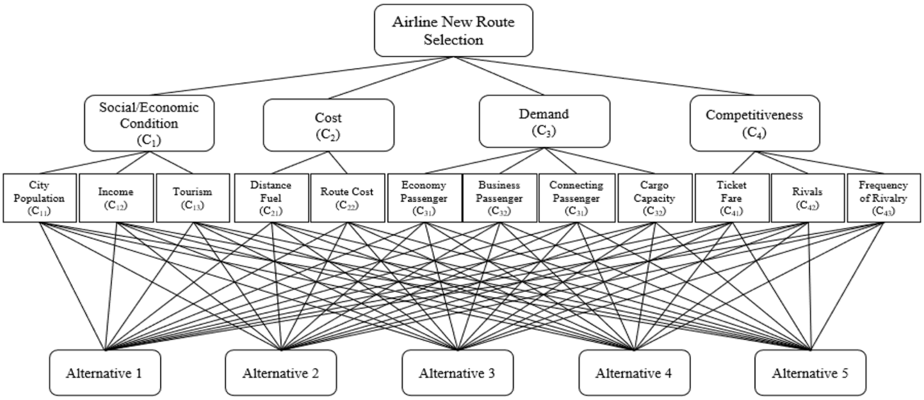
This section applies the proposed model to the route selection of Turkish Airlines as a case study. Turkish Airlines is the flag carrier of Türkiye. Turkish Airlines is the Türkiye’s flag carrier airline. The company was founded in 1933 and has grown to become one of the top international airlines, famous for its vast network, superior services and dedication to the needs of its customers. Turkish Airlines has consistently been awarded the “Best Airline in Europe” by Skytrax, a prestigious international air transport rating organization (Skytrax, 2021). The company has established itself as a significant player in the aviation business, with a fleet size of over 350 aircraft and a wide route network encompassing more than 300 destinations worldwide (Turkish Airlines, 2021). Such a company with mentioned characteristics is a great case study for evaluating the proposed models in this study.

3.5.1 Selecting criteria and alternative routes. In the first stage, the selection criteria and the alternative destinations are identified. Next, the expert decision-makers (DMs) are selected. The experts interviewed in this study are engaged in the airline’s network development department, and all decision-makers had a minimum of five years of experience. The first expert group, which consists of nine decision-makers (from DM_1 to DM_9), has been established. The questionnaire was distributed to decision-makers to evaluate the weighting value of each 12 criteria described previously in Table 4.

Later, another set of five decision-makers (from EDM_1 to EDM_5) was arranged, and they were asked to evaluate five alternative routes with respect to the selection criteria. The hierarchical design of the decision-making problem is shown in Figure 3.

With the help of the initial expert team, five alternative routes were determined. The five alternative routes are as follows: Alternative 1 (SEA), Alternative 2 (DFW), Alternative 3 (DEN), Alternative 4 (SNN) and Alternative 5 (WLG). These routes are illustrated in Figure 4.

3.5.2 Application of interval-valued Pythagorean fuzzy analytical hierarchy process. In the second stage, the weights of selected criteria are calculated using the IV-PF AHP method. Nine network development experts were asked to evaluate these criteria by pairwise comparison with the given linguistic scale.



Source: Authors' own creation

Figure 3. The hierarchy of route selection problem

Source: GreatCircleMap (2022)

Figure 4. The five alternative routes

Step 1. The main criteria listed in Table 4 are subjected to pairwise comparison, and then the sub-criteria are subjected to pairwise comparison by nine experts. The decision-makers used the linguistic terms described in Table 6 to express their pairwise comparison of criteria.

The linguistic terms of the pairwise comparison matrices, which express the evaluation of decision-makers, are transferred into IV-PFNs. The pairwise comparisons of criteria that are transferred into IV PFNs are presented in Appendix 1, Table A1. Due to page limitations, we only provide the pairwise comparison matrix of one set of sub-criteria in Appendix 1, Table A2. Next, the nine individual evaluations were aggregated to represent group decisions and preferences using equation (11). The aggregated group decision matrices of criteria are shown in Tables 3 and 4.

Step 2. The difference matrices, D, are calculated with equations (12) and (13). The difference matrix of the main criteria is presented in Table 8, and the difference matrix of sub-criteria social/economic conditions is presented in Table 9.

Step 3. The interval multiple matrices, ***S***, are calculated with equations (14) and (15). The resulting matrices are shown in Tables 10 and 11.

Step 4. The determinacy values are calculated with equation (16). The determinacy value of the main criteria and the determinacy value of sub-criteria social/economic conditions are presented in Tables 12 and 13, respectively.

Table 8. Difference matrix of main criteria

Main criteria	d_L	d_U	d_L	d_U	d_L	d_U	d_L	d_U
Social/economic conditions	0.000	0.000	−0.159	0.054	−0.515	−0.284	0.077	0.175
Cost	−0.054	0.159	0.000	0.000	0.361	0.509	0.327	0.491
Demand	0.284	0.515	−0.509	−0.361	0.000	0.000	0.274	0.398
Competitiveness	−0.175	−0.077	−0.491	−0.327	−0.398	−0.274	0.000	0.000

Source: Authors' own creation

Table 9. Difference matrix of Sub-criteria (social/economic conditions)

Sub-criteria of social/economic	d_L	d_U	d_L	d_U	d_L	d_U
City population /catchment area	0.000	0.000	−0.373	−0.134	−0.510	−0.348
Income (GDP) and trade	0.134	0.373	0.000	0.000	−0.070	0.196
Tourism potential	0.348	0.510	−0.196	0.070	0.000	0.000

Source: Authors' own creation

Table 10. Interval multiple (S) Matrix of main criteria

Main criteria	s_L	s_U	s_L	s_U	s_L	s_U	s_L	s_U
Social/economic conditions	1.000	1.000	0.577	1.206	0.169	0.374	1.304	1.832
Cost	0.829	1.732	1.000	1.000	3.484	5.799	3.097	5.442
Demand	2.670	5.923	0.172	0.287	1.000	1.000	2.576	3.959
Competitiveness	0.546	0.767	0.184	0.323	0.253	0.388	1.000	1.000

Source: Authors' own creation

Table 11. Interval multiple (S) matrix of sub-criteria (social/economic conditions)

Sub-criteria of social/economic	s_L	s_U	s_L	s_U	s_L	s_U
City population /catchment area	1.000	1.000	0.275	0.629	0.172	0.301
Income (GDP) and trade	1.589	3.632	1.000	1.000	0.784	1.965
Tourism potential	3.327	5.831	0.509	1.275	1.000	1.000

Source: Authors' own creation

Table 12. The determinacy value of main criteria

Main criteria	τ	τ	τ	τ
Social/economic conditions	1.000	0.787	0.769	0.902
Cost	0.787	1.000	0.852	0.837
Demand	0.769	0.852	1.000	0.876
Competitiveness	0.902	0.837	0.876	1.000

Source: Authors' own creation

Table 13. The determinacy value of sub-criteria (social/economic conditions)

Sub-criteria of social/economic conditions	τ	τ	τ
City population / catchment area	1.000	0.761	0.838
Income (GDP) and trade	0.761	1.000	0.734
Tourism potential	0.838	0.734	1.000

Source: Authors' own creation

Step 5. Before weighting the criteria, the normalization matrices, $\boldsymbol{T}$, are calculated with equation (17). The normalization matrix of the main criteria is presented in Table 14, and the normalization matrix of social/economic conditions is given in Table 15.

Step 6. The normalized priority weight of each criterion is calculated with equation (18). The weights of the main criteria, local weights and global weights of sub-criteria are shown below in Table 16.

3.5.3 Application of interval-valued Pythagorean fuzzy weighted aggregated sum product assessment method. This section shows the ranks of five alternative routes with the IV-PF WAPAS method. First, evaluation matrices are created with the performance value of each alternative with respect to each criterion by evaluating five decision-makers using the

Table 14. The normalization matrix of main criteria

Main criteria	T	t	t	t
Social/economic conditions	1.000	0.701	0.209	1.414
Cost	1.007	1.000	3.956	3.573
Demand	3.306	0.196	1.000	2.861
Competitiveness	0.592	0.212	0.280	1.000

Source: Authors' own creation

Table 15. The normalization matrix of Sub-criteria (social/economic conditions)

Sub-criteria of social/economic conditions	T	t	t
City population/catchment area	1.000	0.344	0.198
Income (GDP) and trade	1.986	1.000	1.009
Tourism potential	3.835	0.655	1.000

Source: Authors' own creation

Table 16. Weights of criteria

Main criteria	Weight (%)	Sub-criteria	Local weight (%)	Global weight (%)
Social/economic conditions	15	City population/catchment area	14.0	2.1
		Income (GDP) and trade	36.0	5.4
		Tourism potential	50.0	7.5
Cost	43	Distance (distance*fuel)	73.0	31.4
		Route cost	27.0	11.6
Demand	33	Number of economy passengers	13.0	4.3
		Number of business passengers	10.0	33
		Number of connecting passengers	63.0	20.8
		Cargo capacity	14.0	4.6
Competitiveness	9	Price (fare)	13.0	1.2
		Number of competitor airlines	25.0	2.3
		Frequency of competitors	62.0	5.6

Source: Authors' own creation

linguistic variables in Table 7. The linguistic evaluation of five alternative routes is shown in Table 17.

Next, the evaluation matrix of each expert is transferred into the corresponding IV-PFNs. The combined evaluation matrix of the five decision-makers is shown in Appendix 2, Table A5. After having the aggregated decision matrix of all five experts, the steps of the IV-PF WASPAS method are applied as follows.

Step 1. The decision matrix is normalized with equation (19). The normalized matrix and the maximum values are presented in Table 18.

Step 2. The normalization matrix is transferred into the Pythagorean normalized matrix and is presented in Appendix 2, Table A6.

Step 3. The calculated criteria weights with IV-PF AHP are assigned to the normalized decision matrix, and then WSM (Q_i^1) and WPM (Q_i^2) values are calculated using equations (20) and (21).

The calculation of WSM values for each alternative is shown in Appendix 2, Table A7, whereas Table A8 and Table A9 present the results of WPM calculations.

Step 4: The calculated WSM and WPM values are aggregated using equation (22) with $\lambda = 0{,}5$. The Q_i^1, Q_i^2 and Q_i values in IV-PFNs are given in Table A9. Finally, the model parameter as per equation (23) is calculated as $\lambda^* = 0.471$. Table 19 gives crisp values, Q_i^{cr}, and rankings of alternatives calculated with equation (24) for two different λ. Table 19 shows that the ranking of alternatives does not change.

4. Results and discussion

4.1 Findings of interval-valued Pythagorean fuzzy analytical hierarchy process

The steps of IV-PF AHP are applied to find out the weights of each route selection criteria. Next, the weight of each criterion is calculated. The comparison of the main criteria with weights is shown in Figure 5.

The results show that the cost (43% weight) and demand (33% weight) substantially impact route selection decisions, whereas social/economic conditions (15% weight) and competitiveness (9% weight) are considered less important by the experts.

The effect of route cost has great importance when evaluating a route. There should be a potential demand when selecting a new route so that this would be profitable. Namely, the

Table 17. Linguistic evaluation of five alternative routes

Decision makers	Alternatives	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}	C_{34}	C_{41}	C_{42}	C_{43}
EDM_1	A_1	NG	VG	FG	B	NG	VG	VG	G	NG	VG	VG	FG
	A_2	G	FG	FG	B	NG	VG	VG	FG	FG	VG	VG	FG
	A_3	NG	FG	FG	B	NG	VG	VG	VG	NG	VG	VG	FG
	A_4	B	G	NG	G	G	NG	B	FB	NG	VG	VG	VG
	A_5	B	VG	NG	VB	G	G	FG	G	VB	VG	VG	FG
EDM_2	A_1	FG	VG	VG	NG	FG	G	NG	B	NG	G	NG	NG
	A_2	VG	FG	VG	NG	FG	VG	VG	NG	VG	G	G	NG
	A_3	G	FG	VG	NG	G	VG	G	VG	B	G	G	B
	A_4	B	NG	B	VG	VG	VB	VB	VB	NG	NG	VG	VG
	A_5	B	FG	B	B	VG	FB	B	FB	VB	VG	G	B
EDM_3	A_1	NG	VG	VG	NG	NG	FG	G	G	G	G	B	NG
	A_2	VG	FG	VG	NG	NG	VG	VG	FG	VG	FG	G	NG
	A_3	NG	FG	FG	NG	B	VG	FG	VG	B	FG	NG	FB
	A_4	B	B	VB	VG	G	VB	VB	VB	G	B	VG	FG
	A_5	B	VG	FB	VB	FG	FB	NG	NG	FB	B	G	B
EDM_4	A_1	FG	VG	VG	B	NG	FG	FG	G	G	NG	B	FG
	A_2	VG	FG	FG	B	NG	VG	VG	G	FG	NG	NG	G
	A_3	FG	FG	FG	B	B	VG	FG	VG	B	G	NG	G
	A_4	G	G	NG	VG	FG	B	NG	B	G	VG	VG	VG
	A_5	NG	NG	G	FB	FG	B	G	NG	VG	VG	NG	G
EDM_5	A_1	G	G	VG	FG	G	G	NG	NG	G	G	NG	G
	A_2	FG	FB	FG	FG	VG	NG	G	G	G	FG	FG	FG
	A_3	NG	NG	FG	NG	G	VG	FG	VG	FG	VG	B	FB
	A_4	B	FG	NG	VG	VG	B	VB	B	FG	B	FG	G
	A_5	B	VG	G	B	FG	FG	VG	FG	B	NG	NG	B

Source: Authors’ own creation

Table 18. Normalization matrix and maximum values

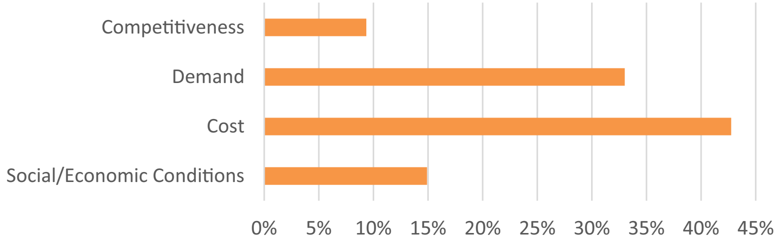
Criteria	A_1	A_2	A_3	A_4	A_5	max	1/max
C_{11}	0.664	0.795	0.627	0.448	0.430	0.795	1.258
C_{12}	0.814	0.664	0.719	0.609	0.776	0.814	1.229
C_{13}	0.833	0.795	0.776	0.466	0.519	0.833	1.201
C_{21}	0.537	0.537	0.501	0.814	0.305	0.814	1.229
C_{22}	0.627	0.664	0.537	0.757	0.757	0.757	1.321
C_{31}	0.738	0.795	0.852	0.359	0.483	0.852	1.174
C_{32}	0.682	0.814	0.757	0.323	0.646	0.814	1.229
C_{33}	0.591	0.682	0.852	0.305	0.573	0.852	1.174
C_{34}	0.627	0.776	0.501	0.646	0.395	0.776	1.289
C_{41}	0.682	0.719	0.757	0.609	0.701	0.757	1.321
C_{42}	0.555	0.701	0.609	0.833	0.664	0.833	1.201
C_{43}	0.664	0.664	0.483	0.795	0.519	0.795	1.259

Source: Authors’ own creation

Table 19. Normalization matrix and maximum values

Alternatives	Q_i^{cr} with $\lambda = 0.5$	Rank	Q_i^{cr} with $\lambda^* = 0.471$	Rank
A_1	0.678	3	0.677	3
A_2	0.709	1	0.708	1
A_3	0.700	2	0.700	2
A_4	0.671	4	0.667	4
A_5	0.557	5	0.555	5

Source: Authors' own creation



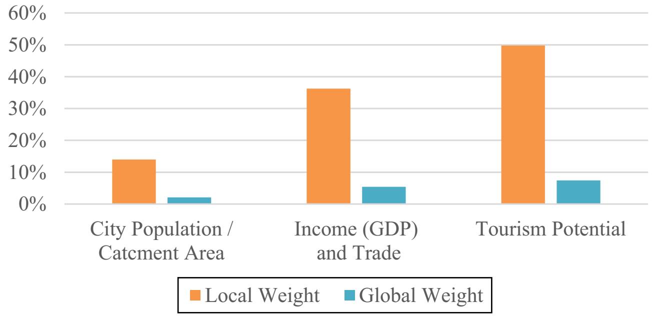
Source: Authors' own creation

Figure 5. Weights of main criteria

passenger demand revenue should cover the route's cost. Considering the studies based on the cost criteria for route selection, one may confirm the outcome of this study. The airline company on which this study was carried out focuses on the cost criterion in the process of route selection decisions. Besides, many other studies on this subject consider the cost criterion as a critical criterion. Gaggero and Piazza (2021) mentioned that cost negatively affected the route selection decision and indicated that the longer route, the lower the probability of entry. Birolini *et al.* (2021) formulated airline network planning, including route selection based on demand and cost with profit maximization. Thekinen *et al.* (2020) emphasized the negative effect of increasing the cost of adding a new route. In line with our findings, Deveci *et al.* (2017) compared 11 criteria, including route distance, with the highest weight. The following section evaluates the significance of each sub-criterion expressed by experts separately.

Social/economic conditions (C_1): Considering the social/economic conditions, tourism potential has the most significant share, with a local weight of 50%. Income/trade is the second with 36%, while the population/catchment area is the last with 14%, as presented in Figure 6. When evaluated over the 12 criteria, tourism potential with a global weight of 7% is the fourth criterion, income/trade with a global weight of 5% is the sixth and population/catchment area with a global weight of 2% is the second lowest criterion.

The obtained results indicate that any route's tourism potential impacts the passenger demand for arrival flights, whereas population and income (GDP) impact the passenger demand for departure flights. The passenger demand, which depends on the city population, would be limited by the number of people who live there. Moreover, the passenger demand, which depends on the GDP, would be the same. On the other hand, the tourism potential of a destination would increase the passenger demand for the route. The developing tourism of a



Source: Authors' own creation

Figure 6. Weights of sub-criteria (social/economic conditions)

city would attract more people to fly there. Both the airline and the destination city would save when more passengers arrive. We can understand this when we compare the importance weights of each criterion.

Cost (C_2): The "cost" as the most important main criterion has the sub-criterion distance (fuel consumption) as the first criterion in both local and global weight, with 73% and 31%, respectively. The other sub-criterion, Route Cost, has 27% local weight, as presented in Figure 7, and stands as the third criterion with 12% global weight.

Since airlines have little control over the cost items, such as fuel and airport charges, the cost criterion can be seen as the most crucial criterion for selecting a new route. Considering the cost structure of airlines, fuel consumption has the most significant share. Fuel is the airline industry's most significant cost item in 2022 at 19.5% (Figure 8). Although airlines use hedging methods to overcome fuel consumption-related problems, this cost item significantly affects the profitability of airlines. Other than fuel consumption, route costs like

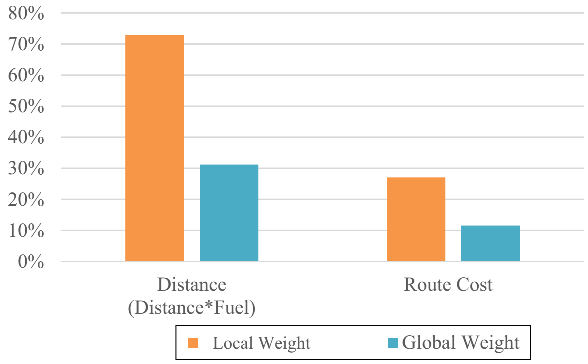


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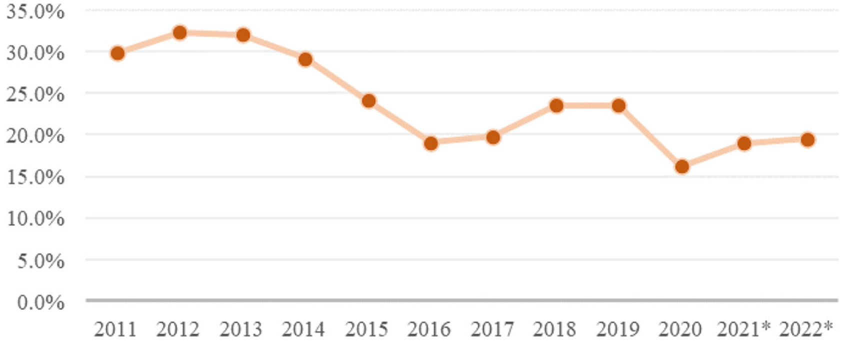
Figure 7. Weights of sub-criteria cost



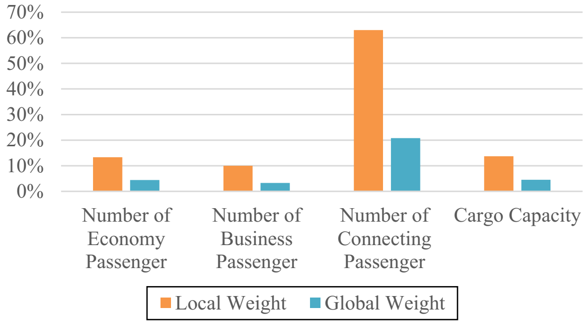
Source: Statista (2022)

Figure 8. Percentage share of expenditure of fuel cost in total cost from 2011–2022

airport expenses and operating crew expenses form a considerable proportion of the total operational cost of airlines.

Demand (C_3): When the second most important main criterion, "demand," is examined, the number of connecting passengers is the first criterion within the group with 63% local weight. Additionally, it is the second criterion over the 12 criteria, with a 21% global weight. Cargo capacity is the second in its group with 14% local weight and is the sixth criterion overall with 5% global weight. The number of economy passengers and the number of business passengers are the seventh and eighth criteria, respectively, with 13% and 10% global weight, as presented in Figure 9.

Despite the dominant share of connecting passengers on the demand side, this situation is different based on the type of airline's network, whether it is a hub-and-spoke airline or only a point-to-point airline. In the hub and spoke network, the airlines not only transport passengers between two points but also connect the passengers via their hub. Such airlines are interested in passenger demand of connecting passengers. In this model, the airlines have a high potential for transit traffic in their hub because of connecting passengers.



Source: Authors' own creation

Figure 9. Weights of sub-criteria demand

On the other hand, a point-to-point network has only the passenger demand between origin and destination (OD) city pairs. In other words, this kind of airline is only interested in transporting the passengers from origin to destination and is not interested in connecting passengers between OD city pairs via another point. It can be stated that the number of connecting passengers has meaningful importance for network airlines, unlike low-cost airlines.

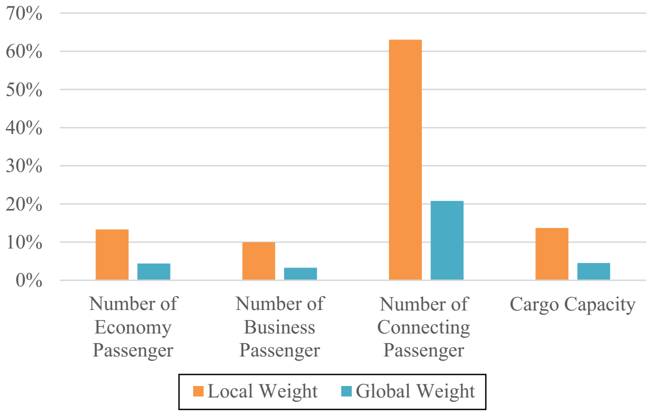
The cargo capacity sub-criteria impacts whether an airline transports air cargo in the holds of passenger aircraft. One could say that nearly every passenger flight carries some cargo in the holds with the passenger baggage. With such a business model, the revenue of that flight would be higher and impact the route's profitability besides the passenger revenue.

Competitiveness (C_4): As mentioned before, competitiveness is the least preferred main criterion, with a weight of 9%. In this main criterion, the frequency of competitors is the first criterion, with 62% local weight, and the fifth criterion overall, with 6% global weight. The number of competitor airlines is the second in its group with 25% local weight and the ninth criterion overall with 2% global weight. The price of the route is the least at both local and global, respectively, with the weight of 13% and 1%, as presented below in Figure 10.

The airline industry is a competitive market in which airlines have to make decisions on fares and frequencies of service in a short amount of time. The price of the route would be created with the demand and supply curve, and the existing competitors would usually determine the fare. If an airline wants to get a market share in a specific route, the number of competitors' flights and the time of competitors' existing flights are essential factors that need to be considered. The more frequent flight of competitors means more alternatives for a passenger. Therefore, this criterion has the most significant share in its group. On the other hand, the effect of the number of competitors would decrease with the alliances between airlines.

4.2 Findings of interval-valued Pythagorean fuzzy weighted aggregated sum product assessment and sensitivity analysis

The steps of IV-PF WASPAS are applied for the ranking of the five routes. The rankings are presented in Table 20.



Source: Authors' own creation

Figure 10. Weights of sub-criteria competitiveness

Table 20. Ranking of five alternative routes (*with* $\lambda = 0.5$)

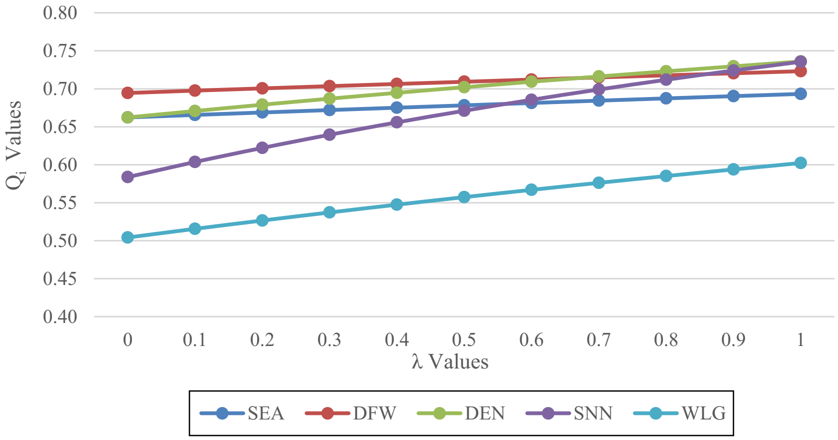
Alternatives routes	Rank
DFW	1
DEN	2
SEA	3
SNN	4
WLG	5

Source: Authors' own creation

Of the five alternative routes, the first three are in the North America region, DFW, DEN and SEA, and the other routes, SNN and WLG, are in Northern Europe and southeastern Australia. Study findings indicate that both cost and demand criteria affect the selection of alternative routes. Although the first three destinations are in the same region with nearly the same distance, the demand factor mainly affects the selection.

As mentioned before, the WASPAS method combines two ranking models, WSM and WPM. The effect of these models on the WASPAS method is balanced with the policy variable, λ, which is between 0 and 1. When the λ is closer to 0, the WPM model is given priority to determine the rankings, whereas the λ is closer to 1, meaning that the WSM model is prioritized. While this study used the λ value of 0.5 (Ayyildiz and Taskin Gumus, 2020; Hatiboglu *et al.*, 2023), the effects of other λ values are graphed in Figure 11. The results show that alternating λ could change the ranking of alternatives (see Table 21).

The ranking of first two alternatives does not change until λ value of 0.6. Moreover, the ranking of A_5 (WLG) does not change with changing λ values. After the λ value of 0.6, the rankings of the first three routes that are in the same region with almost the same distance are alternating. Alternatively, SNN is included in the ranking for λ value after 0.6 because it is closer to the first three routes regarding the distance. The changing of ranking with increasing



Source: Authors' own creation

Figure 11. The effect of changing λ values on route ranking

Table 21. Ranking of alternative with changing of λ values

Λ	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
SEA(A_1)	0.662 (2)	0.666 (3)	0.669 (3)	0.672 (3)	0.675 (3)	0.678 (3)	0.681 (4)	0.684 (4)	0.687 (4)	0.690 (4)	0.693 (4)
DFW(A_2)	0.694 (1)	0.698 (1)	0.701 (1)	0.703 (1)	0.706 (1)	0.709 (1)	0.712 (1)	0.715 (2)	0.718 (2)	0.720 (3)	0.723 (3)
DEN(A_3)	0.662 (2)	0.671 (2)	0.679 (2)	0.687 (2)	0.695 (2)	0.702 (2)	0.709 (2)	0.716 (1)	0.723 (1)	0.730 (1)	0.736 (1)
SNN(A_4)	0.584 (4)	0.604 (4)	0.622 (4)	0.640 (4)	0.656 (4)	0.671 (4)	0.686 (3)	0.699 (3)	0.712 (3)	0.724 (2)	0.736 (1)
WLG(A_5)	0.504 (5)	0.516 (5)	0.527 (5)	0.537 (5)	0.547 (5)	0.557 (5)	0.567 (5)	0.576 (5)	0.585 (5)	0.594 (5)	0.602 (5)

Source: Authors' own creation

λ values is caused by the effect of the distance, in other words, with the effect of cost. Since the literature highlights that the WASPAS method combines WSM and WPM approaches and tries to find a compromise solution between the two, λ is assumed to be 0.5 to reflect this strength. Thus, we suggest relying on the order found when the policy parameter takes this value.

4.3 Managerial implications

The overall findings of this study provide significant strategic insights for airlines to address the complex process of route development. The results show that cost (43%) and demand (33%) are the dominant criteria in selecting new routes. This highlights the critical need for airline management to focus on these elements when making network expansion decisions. For airlines, controlling operational costs such as fuel, labor and airport fees can directly impact profitability, making it a key determinant in route viability. Similarly, assessing market demand through passenger volume forecasts and economic growth indicators is essential for ensuring the sustainability of a new route.

By assigning a substantial weight to demand, the proposed model underscores the necessity of aligning route development with regions that demonstrate clear growth potential. Airline companies can strategically leverage this information to prioritize investments in regions where economic and demographic trends point to increasing travel demand. For instance, airlines can focus on markets with economic signals, like growing incomes or tourism appeal to boost passenger numbers and enhance the profitability of their routes effectively. On the other hand, the moderate influence of social and economic conditions (15%) and competitiveness (9%) suggests that they play a more supportive role in the decision-making process. Airlines should be mindful of these elements but not let them dominate the route selection process. Instead, they can be used as complementary considerations when weighing alternatives. Social and economic factors, such as political stability or infrastructure development, may present long-term risks or opportunities that need to be factored into strategic planning, especially for routes in emerging or unstable markets.

The application of the IV-PF AHP and WASPAS methods provides a systematic approach for decision-makers. By offering a transparent way to evaluate and rank multiple alternatives, the proposed model helps airlines avoid overly subjective judgments, ensuring that decisions are data-driven and aligned with the company's strategic objectives. This is especially critical in the highly competitive and cost-sensitive airline industry, where incorrect decisions can have long-term financial repercussions. The integration of fuzzy logic into the evaluation process enables more flexible and nuanced assessments, which is particularly beneficial when dealing with uncertainty and incomplete information in new markets.

Overall, the proposed model can equip airlines with a more structured and quantifiable way to approach route development, thereby enhancing the accuracy and reliability of their decisions. It not only facilitates short-term operational decisions but also contributes to the long-term strategic planning necessary for sustainable network growth.

5. Conclusion, limitations and future work

This research aimed to design a hybrid MCDM model to find a feasible solution to an airline's new route selection problem. The first part of the model, IV-PF AHP, allows the network developer to evaluate criteria in linguistic terms. The second part of the model, IV-PF WASPAS, ranks the alternative routes and selects the most appropriate alternative.

First, a new hybrid IV-PF AHP and IV-PF WASWAS model for airline route selection problem is designed and applied to a real-world case of a prominent airline company. Second, the model transferred decision-makers' experience from the linguistic world to the numerical one with Pythagorean Fuzzy Numbers. Third, the importance of factors that affect the route selection is determined after a detailed examination and evaluated with the help of IV-PF AHP. Then, the weights of the selected factors are determined. Finally, the alternative airline routes were ranked, and the most suitable route was indicated.

The study results show that many factors affect the airline route selection problem, and each factor does not have equal importance when selecting a new one. According to the experts, cost and demand are the most significant criteria, whereas social/economic conditions and competitiveness are considered less important.

This research introduces a novel MCDM-based model for airline route selection, addressing a gap in the existing literature. By integrating MCDM techniques, the proposed model offers a unique approach to this complex problem. In terms of managerial implications, this research elaborates on a new method for airline management to deal with network development decisions. The proposed model can help airlines' network planning department in evaluating all available options and making educated and accurate decisions.

In addition to the operational and financial benefits for airlines, the proposed model can provide considerable societal benefits. Efficient route planning can significantly improve the quality of life for communities and areas that airlines fly to them. By prioritizing routes according to demand and economic potential, airlines enhance profitability while fostering regional accessibility and economic development. The optimization of routes significantly enhances accessibility to previously underserved or rural areas. When airlines introduce new routes that align with high demand, it can stimulate economic growth in these areas by fostering tourism, business travel and trade. This can create jobs, encourage investment and promote regional development for these areas. Moreover, route optimization helps reduce the environmental footprint of air travel. By selecting the most efficient routes and considering factors such as load factors and operational costs, airlines can minimize unnecessary fuel consumption and reduce emissions. In addition, public perception is also shaped by the convenience and affordability of provided service. Well-optimized routes that reflect consumer demand contribute to a more positive travel experience by offering greater flight frequency, reduced travel time and lower ticket prices due to improved operational efficiency. This improves customer satisfaction and loyalty, which can strengthen the airline's brand image and its relationship in the long term.

While this study uses Turkish Airlines as a case to demonstrate the application of the proposed model for route selection, the findings and methodology have broader implications for the airline industry. The core components of the model are designed in such a way that it can be adaptable to varying market conditions and airline business models. One key aspect of the model's adaptability lies in its flexibility in weighting selection criteria. Although the study found that cost (43%) and demand (33%) are the most influential factors for Turkish Airlines, these weights can be easily recalibrated to reflect the priorities of different airlines. For instance, low-cost carriers may assign even greater importance to cost-related factors, while full-service carriers such as Turkish Airlines might prioritize customer experience, network connectivity or even sustainability initiatives. Similarly, airlines that operate in highly competitive markets or emerging economies may weigh competitiveness or socioeconomic conditions differently to align with their strategic objectives. Moreover, the criteria used in this study – such as cost, demand, social/economic conditions and competitiveness – are universal factors relevant to route selection in most airline operations. However, the model's framework allows for the inclusion of additional criteria that might be specific to particular markets or airlines.

This research was based on an interview with the network development department of a full-service network airline. One of the limitations of this study is that the decision-makers could have similar perspectives since they all work in the same organization. The application of the model to different airlines would confirm its validity. Similarly, this study can be tested in different settings, such as different airline business models, regions, companies and fleet compositions. Furthermore, although the study was conducted after the COVID-19 Pandemic, the data collected from the airline was just from the period before the Pandemic. Since the entire market dynamic has disrupted by the COVID-19, no reliable and recent data was available. Thus, new studies may focus these new market dynamics. Finally, hybridizing other recent MCDM methods may be one of the future research directions. The output of the proposed model can be used as input for some decisions on the operational level, such as flight frequency and slot allocation decisions.

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Appendix 1

Table A1. The pairwise comparison matrix of main criteria with IV-PFNs

Decision makers	Main Criteria	Social /economic conditions				Cost				Demand				Competitiveness			
		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
DM_1	Social/economic conditions	0.1965	0.1965	0.1965	0.1965	0.55	0.65	0.35	0.45	0.2	0.35	0.65	0.8	0.1	0.2	0.8	0.9
	Cost	0.35	0.45	0.55	0.65	0.1965	0.1965	0.1965	0.1965	0.55	0.65	0.35	0.45	0.2	0.35	0.65	0.8
	Demand	0.65	0.8	0.2	0.35	0.35	0.45	0.55	0.65	0.1965	0.1965	0.1965	0.1965	0.45	0.55	0.45	0.55
	Competitiveness	0.8	0.9	0.1	0.2	0.65	0.8	0.2	0.35	0.45	0.55	0.45	0.55	0.1965	0.1965	0.1965	0.1965
DM_2	Social/Economic Conditions	0.1965	0.1965	0.1965	0.1965	0.2	0.35	0.65	0.8	0.1	0.2	0.8	0.9	0.2	0.35	0.65	0.8
	Cost	0.65	0.8	0.2	0.35	0.1965	0.1965	0.1965	0.1965	0.55	0.65	0.35	0.45	0.45	0.55	0.45	0.55
	Demand	0.8	0.9	0.1	0.2	0.35	0.45	0.55	0.65	0.1965	0.1965	0.1965	0.1965	0.35	0.45	0.55	0.65
	Competitiveness	0.65	0.8	0.2	0.35	0.45	0.55	0.45	0.55	0.55	0.65	0.35	0.45	0.1965	0.1965	0.1965	0.1965
DM_3	Social/Economic Conditions	0.1965	0.1965	0.1965	0.1965	0.45	0.55	0.45	0.55	0.35	0.45	0.55	0.65	0.55	0.65	0.35	0.45
	Cost	0.45	0.55	0.45	0.55	0.1965	0.1965	0.1965	0.1965	0.45	0.55	0.45	0.55	0.35	0.45	0.55	0.65
	Demand	0.55	0.65	0.35	0.45	0.45	0.55	0.45	0.55	0.1965	0.1965	0.1965	0.1965	0.65	0.8	0.2	0.35
	Competitiveness	0.35	0.45	0.55	0.65	0.55	0.65	0.35	0.45	0.2	0.35	0.65	0.8	0.1965	0.1965	0.1965	0.1965
DM_4	Social/Economic Conditions	0.1965	0.1965	0.1965	0.1965	0.35	0.45	0.55	0.65	0.1	0.2	0.8	0.9	0.2	0.35	0.65	0.8
	Cost	0.55	0.65	0.35	0.45	0.1965	0.1965	0.1965	0.1965	0.45	0.55	0.45	0.55	0.55	0.65	0.35	0.45
	Demand	0.8	0.9	0.1	0.2	0.45	0.55	0.45	0.55	0.1965	0.1965	0.1965	0.1965	0.35	0.45	0.55	0.65
	Competitiveness	0.65	0.8	0.2	0.35	0.35	0.45	0.55	0.65	0.55	0.65	0.35	0.45	0.1965	0.1965	0.1965	0.1965
DM_5	Social/economic conditions	0.1965	0.1965	0.1965	0.1965	0.45	0.55	0.45	0.55	0.2	0.35	0.65	0.8	0.35	0.45	0.55	0.65
	Cost	0.45	0.55	0.45	0.55	0.1965	0.1965	0.1965	0.1965	0.65	0.8	0.2	0.35	0.9	1	0	0
	Demand	0.65	0.8	0.2	0.35	0.2	0.35	0.65	0.8	0.1965	0.1965	0.1965	0.1965	0.55	0.65	0.35	0.45
	Competitiveness	0.55	0.65	0.35	0.45	0	0	0.9	1	0.35	0.45	0.55	0.65	0.1965	0.1965	0.1965	0.1965
DM_6	Social/Economic Conditions	0.1965	0.1965	0.1965	0.1965	0.45	0.55	0.45	0.55	0.1	0.2	0.8	0.9	0.2	0.35	0.65	0.8
	Cost	0.45	0.55	0.45	0.55	0.1965	0.1965	0.1965	0.1965	0.8	0.9	0.1	0.2	0.8	0.9	0.1	0.2
	Demand	0.8	0.9	0.1	0.2	0.1	0.2	0.8	0.9	0.1965	0.1965	0.1965	0.1965	0.55	0.65	0.35	0.45
	Competitiveness	0.65	0.8	0.2	0.35	0.1	0.2	0.8	0.9	0.35	0.45	0.55	0.65	0.1965	0.1965	0.1965	0.1965

(*continued*)

Table A1. Continued

Decision makers	Main Criteria	Social /economic conditions				Cost				Demand				Competitiveness			
		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
DM_7	Social/Economic Conditions	0.1965	0.1965	0.1965	0.1965	0.45	0.55	0.45	0.55	0.35	0.45	0.55	0.65	0.2	0.35	0.65	0.8
	Cost	0.45	0.55	0.45	0.55	0.1965	0.1965	0.1965	0.1965	0.9	1	0	0	0.65	0.8	0.2	0.35
	Demand	0.55	0.65	0.35	0.45	0	0	0.9	1	0.1965	0.1965	0.1965	0.1965	0.55	0.65	0.35	0.45
	Competitiveness	0.65	0.8	0.2	0.35	0.2	0.35	0.65	0.8	0.35	0.45	0.55	0.65	0.1965	0.1965	0.1965	0.1965
DM_8	Social/Economic Conditions	0.1965	0.1965	0.1965	0.1965	0.45	0.55	0.45	0.55	0.55	0.65	0.35	0.45	0.9	1	0	0
	Cost	0.45	0.55	0.45	0.55	0.1965	0.1965	0.1965	0.1965	0.55	0.65	0.35	0.45	0.9	1	0	0
	Demand	0.35	0.45	0.55	0.65	0.35	0.45	0.55	0.65	0.1965	0.1965	0.1965	0.1965	0.9	1	0	0
	Competitiveness	0	0	0.9	1	0	0	0.9	1	0	0	0.9	1	0.1965	0.1965	0.1965	0.1965
DM_9	Social/Economic Conditions	0.1965	0.1965	0.1965	0.1965	0.45	0.55	0.45	0.55	0.2	0.35	0.65	0.8	0.35	0.45	0.55	0.65
	Cost	0.45	0.55	0.45	0.55	0.1965	0.1965	0.1965	0.1965	0.65	0.8	0.2	0.35	0.9	1	0	0
	Demand	0.65	0.8	0.2	0.35	0.2	0.35	0.65	0.8	0.1965	0.1965	0.1965	0.1965	0.55	0.65	0.35	0.45
	Competitiveness	0.55	0.65	0.35	0.45	0	0	0.9	1	0.35	0.45	0.55	0.65	0.1965	0.1965	0.1965	0.1965

Source: Authors' own creation

Table A2. The pairwise comparison matrix of social/economic conditions sub-criteria criteria with IV-PFNs

Decision makers	Social/economic conditions	City population/catchment area				Income (GDP) and trade				Tourism potential			
		μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U
DM$_1$	City population / Catchment Area	0.1965	0.1965	0.1965	0.1965	0.1	0.2	0.8	0.9	0	0	0.9	1
	Income (GDP) and Trade	0.8	0.9	0.1	0.2	0.1965	0.1965	0.1965	0.1965	0.1	0.2	0.8	0.9
	Tourism potential	0.9	1	0	0	0.8	0.9	0.1	0.2	0.1965	0.1965	0.1965	0.1965
DM$_2$	City Population / Catchment Area	0.1965	0.1965	0.1965	0.1965	0.8	0.9	0.1	0.2	0.55	0.65	0.35	0.45
	Income (GDP) and Trade	0.1	0.2	0.8	0.9	0.1965	0.1965	0.1965	0.1965	0.2	0.35	0.65	0.8
	Tourism potential	0.35	0.45	0.55	0.65	0.65	0.8	0.2	0.35	0.1965	0.1965	0.1965	0.1965
DM$_3$	City Population / Catchment Area	0.1965	0.1965	0.1965	0.1965	0.35	0.45	0.55	0.65	0.2	0.35	0.65	0.8
	Income (GDP) and Trade	0.55	0.65	0.35	0.45	0.1965	0.1965	0.1965	0.1965	0.35	0.45	0.55	0.65
	Tourism potential	0.65	0.8	0.2	0.35	0.55	0.65	0.35	0.45	0.1965	0.1965	0.1965	0.1965
DM$_4$	City Population / Catchment Area	0.1965	0.1965	0.1965	0.1965	0.2	0.35	0.65	0.8	0.2	0.35	0.65	0.8
	Income (GDP) and Trade	0.65	0.8	0.2	0.35	0.1965	0.1965	0.1965	0.1965	0.2	0.35	0.65	0.8
	Tourism potential	0.65	0.8	0.2	0.35	0.65	0.8	0.2	0.35	0.1965	0.1965	0.1965	0.1965
DM$_5$	City Population / Catchment Area	0.1965	0.1965	0.1965	0.1965	0.1	0.2	0.8	0.9	0.2	0.35	0.65	0.8
	Income (GDP) and Trade	0.8	0.9	0.1	0.2	0.1965	0.1965	0.1965	0.1965	0.65	0.8	0.2	0.35
	Tourism potential	0.65	0.8	0.2	0.35	0.2	0.35	0.65	0.8	0.1965	0.1965	0.1965	0.1965
DM$_6$	City Population / Catchment Area	0.1965	0.1965	0.1965	0.1965	0.2	0.35	0.65	0.8	0.35	0.45	0.55	0.65
	Income (GDP) and Trade	0.65	0.8	0.2	0.35	0.1965	0.1965	0.1965	0.1965	0.8	0.9	0.1	0.2
	Tourism potential	0.55	0.65	0.35	0.45	0.1	0.2	0.8	0.9	0.1965	0.1965	0.1965	0.1965

(*continued*)

Table A2. Continued

Decision makers	Social/economic conditions	City population/catchment area				Income (GDP) and trade				Tourism potential			
		μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U
DM_7	City Population / Catchment Area	0.1965	0.1965	0.1965	0.1965	0.2	0.35	0.65	0.8	0.1	0.2	0.8	0.9
	Income (GDP) and Trade	0.65	0.8	0.2	0.35	0.1965	0.1965	0.1965	0.1965	0.65	0.8	0.2	0.35
	Tourism potential	0.8	0.9	0.1	0.2	0.2	0.35	0.65	0.8	0.1965	0.1965	0.1965	0.1965
DM_8	City Population / Catchment Area	0.1965	0.1965	0.1965	0.1965	0.35	0.45	0.55	0.65	0.55	0.65	0.35	0.45
	Income (GDP) and Trade	0.55	0.65	0.35	0.45	0.1965	0.1965	0.1965	0.1965	0.65	0.8	0.2	0.35
	Tourism potential	0.35	0.45	0.55	0.65	0.2	0.35	0.65	0.8	0.1965	0.1965	0.1965	0.1965
DM_9	City Population / Catchment Area	0.1965	0.1965	0.1965	0.1965	0.35	0.45	0.55	0.65	0.2	0.35	0.65	0.8
	Income (GDP) and Trade	0.55	0.65	0.35	0.45	0.1965	0.1965	0.1965	0.1965	0.65	0.8	0.2	0.35
	Tourism potential	0.65	0.8	0.2	0.35	0.2	0.35	0.65	0.8	0.1965	0.1965	0.1965	0.1965

Source: Authors' own creation

Table A3. Aggregating pairwise comparison of main criteria

	Social /economic conditions				Cost				Demand				Competitiveness			
	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
Social/economic conditions	0.1965	0.1965	0.1965	0.1965	0.4089	0.5211	0.4661	0.5712	0.2011	0.3290	0.6266	0.7453	0.2773	0.4186	0.0000	0.0000
Cost	0.4661	0.5712	0.4089	0.5211	0.1965	0.1965	0.1965	0.1965	0.6011	0.7134	0.0000	0.0000	0.5721	0.7004	0.0000	0.0000
Demand	0.6266	0.7453	0.2011	0.3290	0.0000	0.0000	0.6011	0.7134	0.1965	0.1965	0.1965	0.1965	0.5235	0.6312	0.0000	0.0000
Competitiveness	0.0000	0.0000	0.2773	0.4186	0.0000	0.0000	0.5721	0.7004	0.0000	0.0000	0.5235	0.6312	0.1965	0.1965	0.1965	0.1965

Source: Authors’ own creation

Table A4. Aggregating pairwise comparison of sub-criteria

	City population/catchment area				Income (GDP) and trade				Tourism potential			
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U
City pop./catchment area	0.1965	0.1965	0.1965	0.1965	0.2410	0.3733	0.5229	0.6569	0.0000	0.0000	0.5900	0.7145
Income (GDP) and trade	0.5229	0.6569	0.2410	0.3733	0.1965	0.1965	0.1965	0.1965	0.3881	0.5424	0.3141	0.4702
Tourism potential	0.5900	0.7145	0.0000	0.0000	0.3141	0.4702	0.3881	0.5424	0.1965	0.1965	0.1965	0.1965

Source: Authors’ own creation

Appendix 2

Table A5. Group decision matrix of alternative route evaluation

	A$_1$				A$_2$				A$_3$				A$_4$				A$_5$			
x_{ij}	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	μ_L	μ_U	v_L	v_U
C$_{11}$	0.600	0.700	0.300	0.400	0.740	0.840	0.160	0.260	0.560	0.660	0.340	0.440	0.360	0.460	0.540	0.640	0.340	0.440	0.560	0.660
C$_{12}$	0.760	0.860	0.140	0.240	0.600	0.700	0.300	0.400	0.660	0.760	0.240	0.340	0.540	0.640	0.360	0.460	0.720	0.820	0.180	0.280
C$_{13}$	0.780	0.880	0.120	0.220	0.740	0.840	0.160	0.260	0.720	0.820	0.180	0.280	0.380	0.480	0.520	0.620	0.440	0.540	0.460	0.560
C$_{21}$	0.460	0.560	0.440	0.540	0.460	0.560	0.440	0.540	0.420	0.520	0.480	0.580	0.760	0.860	0.140	0.240	0.200	0.300	0.700	0.800
C$_{22}$	0.560	0.660	0.340	0.440	0.600	0.700	0.300	0.400	0.460	0.560	0.440	0.540	0.700	0.800	0.200	0.300	0.700	0.800	0.200	0.300
C$_{31}$	0.680	0.780	0.220	0.320	0.740	0.840	0.160	0.260	0.800	0.900	0.100	0.200	0.260	0.360	0.640	0.740	0.400	0.500	0.500	0.600
C$_{32}$	0.620	0.720	0.280	0.380	0.760	0.860	0.140	0.240	0.700	0.800	0.200	0.300	0.220	0.320	0.680	0.780	0.580	0.680	0.320	0.420
C$_{33}$	0.520	0.620	0.380	0.480	0.620	0.720	0.280	0.380	0.800	0.900	0.100	0.200	0.200	0.300	0.700	0.800	0.500	0.600	0.400	0.500
C$_{34}$	0.560	0.660	0.340	0.440	0.720	0.820	0.180	0.280	0.420	0.520	0.480	0.580	0.580	0.680	0.320	0.420	0.300	0.400	0.600	0.700
C$_{41}$	0.620	0.720	0.280	0.380	0.660	0.760	0.240	0.340	0.700	0.800	0.200	0.300	0.540	0.640	0.360	0.460	0.640	0.740	0.260	0.360
C$_{42}$	0.480	0.580	0.420	0.520	0.640	0.740	0.260	0.360	0.540	0.640	0.360	0.460	0.780	0.880	0.120	0.220	0.600	0.700	0.300	0.400
C$_{43}$	0.600	0.700	0.300	0.400	0.600	0.700	0.300	0.400	0.400	0.500	0.500	0.600	0.740	0.840	0.160	0.260	0.440	0.540	0.460	0.560

Source: Authors’ own creation

Table A6. Pythagorean fuzzy normalized decision matrix

	A_1				A_2				A_3				A_4				A_5			
r_{ij}	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	μ_L	μ_U	v_L	v_U
C_{11}	0.66	0.76	0.22	0.32	0.79	0.89	0.10	0.18	0.61	0.72	0.26	0.36	0.40	0.51	0.46	0.57	0.38	0.49	0.48	0.59
C_{12}	0.81	0.90	0.09	0.17	0.65	0.75	0.23	0.32	0.71	0.81	0.17	0.27	0.59	0.69	0.28	0.38	0.77	0.86	0.12	0.21
C_{13}	0.82	0.91	0.08	0.16	0.78	0.88	0.11	0.20	0.76	0.86	0.13	0.22	0.41	0.52	0.46	0.56	0.48	0.58	0.39	0.50
C_{21}	0.50	0.61	0.36	0.47	0.50	0.61	0.36	0.47	0.46	0.57	0.41	0.51	0.81	0.90	0.09	0.17	0.22	0.33	0.65	0.76
C_{22}	0.63	0.73	0.24	0.34	0.67	0.77	0.20	0.30	0.52	0.63	0.34	0.44	0.77	0.86	0.12	0.20	0.77	0.86	0.12	0.20
C_{31}	0.72	0.82	0.17	0.26	0.78	0.87	0.12	0.21	0.84	0.93	0.07	0.15	0.28	0.39	0.59	0.70	0.43	0.54	0.44	0.55
C_{32}	0.67	0.77	0.21	0.30	0.81	0.90	0.09	0.17	0.75	0.85	0.14	0.23	0.24	0.35	0.62	0.74	0.63	0.73	0.25	0.34
C_{33}	0.56	0.66	0.32	0.42	0.66	0.76	0.22	0.32	0.84	0.93	0.07	0.15	0.22	0.32	0.66	0.77	0.54	0.64	0.34	0.44
C_{34}	0.62	0.72	0.25	0.35	0.78	0.87	0.11	0.19	0.47	0.58	0.39	0.50	0.64	0.74	0.23	0.33	0.34	0.45	0.52	0.63
C_{41}	0.69	0.79	0.19	0.28	0.73	0.82	0.15	0.24	0.77	0.86	0.12	0.20	0.60	0.71	0.26	0.36	0.71	0.81	0.17	0.26
C_{42}	0.52	0.62	0.35	0.46	0.68	0.78	0.20	0.29	0.58	0.68	0.29	0.39	0.82	0.91	0.08	0.16	0.64	0.74	0.24	0.33
C_{43}	0.66	0.76	0.22	0.32	0.66	0.76	0.22	0.32	0.44	0.55	0.42	0.53	0.79	0.89	0.10	0.18	0.49	0.59	0.38	0.48

Source: Authors’ own creation

Table A7. The calculation of WSM

WSM	A$_1$				A$_2$				A$_3$				A$_4$				A$_5$			
$w_j r_{ij}$	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	μ_L	μ_U	v_L	v_U
C$_{11}$	0.11	0.13	0.97	0.98	0.14	0.18	0.95	0.97	0.10	0.12	0.97	0.98	0.06	0.08	0.98	0.99	0.06	0.08	0.98	0.99
C$_{12}$	0.24	0.29	0.88	0.91	0.17	0.21	0.92	0.94	0.19	0.24	0.91	0.93	0.15	0.19	0.93	0.95	0.22	0.27	0.89	0.92
C$_{13}$	0.28	0.35	0.83	0.87	0.26	0.32	0.85	0.89	0.25	0.31	0.86	0.89	0.12	0.15	0.94	0.96	0.14	0.17	0.93	0.95
C$_{21}$	0.30	0.37	0.73	0.79	0.30	0.37	0.73	0.79	0.27	0.34	0.75	0.81	0.53	0.63	0.47	0.58	0.12	0.19	0.87	0.92
C$_{22}$	0.24	0.29	0.85	0.88	0.26	0.31	0.83	0.87	0.19	0.24	0.88	0.91	0.31	0.38	0.78	0.83	0.31	0.38	0.78	0.83
C$_{31}$	0.18	0.22	0.92	0.94	0.20	0.25	0.91	0.93	0.23	0.29	0.89	0.92	0.06	0.08	0.98	0.98	0.09	0.12	0.96	0.97
C$_{32}$	0.14	0.17	0.95	0.96	0.19	0.23	0.92	0.94	0.16	0.20	0.94	0.95	0.04	0.07	0.98	0.99	0.13	0.16	0.95	0.97
C$_{33}$	0.27	0.33	0.79	0.84	0.33	0.40	0.73	0.79	0.47	0.58	0.57	0.67	0.10	0.15	0.92	0.95	0.26	0.32	0.80	0.84
C$_{34}$	0.15	0.18	0.94	0.95	0.20	0.25	0.90	0.93	0.11	0.13	0.96	0.97	0.15	0.19	0.94	0.95	0.07	0.10	0.97	0.98
C$_{41}$	0.09	0.11	0.98	0.98	0.10	0.12	0.98	0.98	0.10	0.13	0.97	0.98	0.08	0.09	0.98	0.99	0.09	0.11	0.98	0.98
C$_{42}$	0.09	0.11	0.98	0.98	0.12	0.15	0.96	0.97	0.10	0.12	0.97	0.98	0.16	0.20	0.94	0.96	0.11	0.14	0.97	0.97
C$_{43}$	0.18	0.22	0.92	0.94	0.18	0.22	0.92	0.94	0.11	0.14	0.95	0.96	0.24	0.29	0.88	0.91	0.12	0.16	0.95	0.96

Source: Authors’ own creation

Table A8. Calculation of WPM

WPM		A$_1$				A$_2$				A$_3$				A$_4$				A$_5$		
$(r_{ij})^{w_j}$	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	μ_L	μ_U	v_L	v_U
C$_{11}$	0.991	0.994	0.032	0.047	0.995	0.997	0.014	0.027	0.990	0.993	0.038	0.05	0.981	0.986	0.070	0.090	0.980	0.985	0.074	0.095
C$_{12}$	0.989	0.994	0.021	0.040	0.977	0.985	0.054	0.077	0.982	0.989	0.040	0.063	0.972	0.980	0.068	0.093	0.986	0.992	0.028	0.049
C$_{13}$	0.986	0.993	0.021	0.044	0.982	0.990	0.030	0.055	0.980	0.989	0.035	0.060	0.937	0.953	0.131	0.167	0.947	0.961	0.111	0.145
C$_{21}$	0.807	0.857	0.209	0.273	0.807	0.857	0.209	0.273	0.785	0.838	0.233	0.301	0.936	0.967	0.050	0.097	0.625	0.708	0.393	0.486
C$_{22}$	0.947	0.964	0.083	0.118	0.954	0.970	0.070	0.103	0.927	0.947	0.118	0.158	0.970	0.983	0.041	0.070	0.970	0.983	0.041	0.070
C$_{31}$	0.986	0.991	0.036	0.056	0.989	0.994	0.024	0.044	0.992	0.997	0.014	0.032	0.946	0.959	0.137	0.172	0.964	0.973	0.098	0.125
C$_{32}$	0.987	0.991	0.038	0.056	0.993	0.997	0.016	0.032	0.991	0.995	0.025	0.042	0.955	0.966	0.126	0.159	0.985	0.990	0.045	0.064
C$_{33}$	0.885	0.917	0.150	0.200	0.917	0.944	0.103	0.150	0.963	0.984	0.031	0.069	0.727	0.791	0.334	0.413	0.878	0.911	0.159	0.211
C$_{34}$	0.979	0.985	0.054	0.076	0.989	0.994	0.023	0.042	0.967	0.976	0.086	0.112	0.980	0.987	0.050	0.071	0.952	0.964	0.118	0.151
C$_{41}$	0.995	0.997	0.021	0.032	0.996	0.998	0.017	0.027	0.997	0.998	0.013	0.023	0.994	0.996	0.029	0.041	0.996	0.997	0.019	0.029
C$_{42}$	0.985	0.989	0.055	0.073	0.991	0.994	0.030	0.046	0.988	0.991	0.046	0.062	0.995	0.998	0.012	0.025	0.990	0.993	0.036	0.052
C$_{43}$	0.976	0.984	0.053	0.078	0.976	0.984	0.053	0.078	0.954	0.966	0.105	0.136	0.987	0.993	0.024	0.044	0.959	0.970	0.094	0.123

Source: Authors' own creation

Table A9. WSM. WPM and aggregated Pythagorean fuzzy values of each alternative

	A_1				A_2				A_3				A_4				A_5			
	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	μ_L	μ_U	v_L	v_U
Q_i^1	0.627	0.734	0.249	0.353	0.661	0.765	0.218	0.319	0.671	0.773	0.207	0.318	0.673	0.782	0.214	0.326	0.529	0.636	0.358	0.471
Q_i^1	0.595	0.698	0.290	0.388	0.631	0.733	0.259	0.354	0.596	0.701	0.304	0.399	0.509	0.625	0.414	0.517	0.416	0.531	0.470	0.582
Q_i	0.612	0.717	0.269	0.370	0.646	0.750	0.238	0.336	0.636	0.746	0.251	0.357	0.603	0.717	0.297	0.411	0.477	0.589	0.410	0.524

Source: Authors’ own creation