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Spaceport Selection Using a Novel Hybrid Pythagorean Fuzzy AHP & TOPSIS Based Methodology: A Case Study of Turkey

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Abstract

Space technologies have continued their development accelerated with Sputnik 1 launching into space in 1957 and the USA-USSR competition. The period that is until today, due to the increase in studies about space research and space technology, has been called the space age. Turkey has launched 12 satellites from the launch of TURKSAT 1A on December 24, 1994, until today, and it has six active satellites. In this study, a hybrid PF AHP-PF TOPSIS approach has been developed on which spaceport would be the most appropriate choice for launching satellites when the political and diplomatic conditions are ignored for Turkey because of the use of various spaceports for the previous launchings. This study makes a concrete contribution to the literature through its novelty that this is the first time a spaceport selection problem is addressed in Pythagorean Fuzzy Environment with the well-described criteria. In virtue of the recent technological developments in space science, new opinions that new spaceports worldwide will be built to maintain the momentum of the space tourism industry emerging recently have been proposed. In this regard, this study serves as a guideline to decide which criteria to consider more carefully in order to build a new spaceport.

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Pisagor Bulanık Ortamda Yeni Bir Melez AHP TOPSIS Tabanlı Yöntemle Uzay İstasyonu Seçimi: Türkiye'den Bir Vaka Çalışması

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Öz

Uzay teknolojileri, 1957'de Sputnik 1'in uzaya fırlatılması ve ABD-SSCB rekabeti ile hızlanarak gelişimini sürdürdü. Günümüze kadar olan dönem uzay araştırmaları ve uzay teknolojisi ile ilgili çalışmaların artması nedeniyle uzay çağı olarak adlandırılmıştır. Türkiye, 24 Aralık 1994 tarihinde TÜRKSAT 1A'nın fırlatılmasından bugüne kadar 12 uydu fırlatmıştır ve altı aktif uydusu bulunmaktadır. Bu çalışmada, daha önceki fırlatmalar için çeşitli uzay limanlarının kullanılması nedeniyle Türkiye için siyasi ve diplomatik koşullar göz ardı edildiğinde, uyduların fırlatılması için hangi uzay limanının en uygun seçim olacağını belirlemek amacıyla melez bir PF AHP-PF TOPSIS yaklaşımı geliştirilmiştir. Bu çalışma, Pisagor bulanık ortamda ilk kez bir uzay limanı seçim probleminin iyi tanımlanmış kriterlerle ele alınmasıyla literatüre somut bir katkı sağlamaktadır. Uzay bilimindeki son teknolojik gelişmeler sayesinde, son zamanlarda ortaya çıkan uzay turizmi endüstrisinin momentumunu korumak için dünya çapında yeni uzay limanlarının inşa edileceğine dair yeni görüşler öne sürüldü. Bu bağlamda, bu çalışma, yeni bir uzay limanı inşa etmek için hangi kriterlerin daha dikkatli ele alınacağına karar vermek için bir kılavuz görevi görmektedir.

1. INTRODUCTION

Developments in space technologies have significantly speeded up since the middle of the 20th century. These technological advances have directly contributed to the emergence of new ways and means of better observing and understanding the universe. Governmental and private enterprises have also encouraged many research projects to design and build high-efficiency and low-cost satellite systems orbiting around the Earth to achieve different civil and military missions. The main aim of these attempts is to improve the accessibility, affordability, and quality of the satellite-based services including communication, navigation, weather monitoring, earth observation, etc. According to the latest figures prepared by ESA's Space Debris Office, 10490 satellites have launched into Earth's orbit since the space age began in 1957 and about 3300 of them are still operating [1].

The recent studies demonstrate that many developed countries are now focused on adapting their space programs for nascent space activities, including space tourism, space mining, and space colonization [2]. Therefore, it seems reasonable to consider that these newly emerging sectors will shape the space age's future. Meanwhile, middle-income countries have also made significant progress in the space sector. For example, in the African Space Strategy introduced in 2016 an effective cooperation policy was proposed to strengthen the economic power and qualified human resources in Africa, thereby providing the sustainability of space technology development [3]. Considering all these recent developments in technology and politics, it is possible to foresee that more satellites will be launched in the upcoming years. Although these growing trends have received a big welcome, the ability of a country destitute of a spaceport to launch space vehicles into space relies on the use of one of the existing spaceports. Therefore, a very painful spaceport selection process must be performed to decide the most feasible spaceport among the possible alternatives. This tough challenge gives rise to some technical and economic problems for those suffering from this infrastructural deprivation. The diversity of different factors induces a high level of complexity in the selection process.

In previous studies [4-6], researchers were mainly interested in determining the necessary characteristics for selecting a site to construct a spaceport. The site selection of a spaceport is one of the most critical decisions to ensure a sustainable space program, complete space missions successfully, and minimize the risk of damage to the environment in case of failure. According to a previous study on the decision-making (D-M) process of selecting a spaceport site in Indonesia [7], five specific criteria were defined as follows: i) geographical location, ii) operation & infrastructure, iii) safety & security, iv) economy and v) meteorology. Besides, each main criterion is divided into several sub-criteria to evaluate the feasibility of each alternative carefully.

The most important main criterion is generally considered as the geographical location [8]. The underlying reason for this is that proximity to the equator increases the payload capacity of space vehicles in low inclination orbits. Besides, a space vehicle launches from a base station close to the equator renders it possible that space vehicles orbit in the direction of the Earth's spin (from west to east) without the need for extreme orbit correction maneuvers. The minimum requirement for executing correction maneuvers results in less energy consumption and longer satellite life. On the other hand, there are some cases in which the proximity to the equator is not always favorable for launching [9, 10]. For example, the success of launching a space vehicle into polar orbit primarily relies on the proximity of poles or the maximum Earth surface velocity at the equator is not of benefit to launching a spacecraft due westward. As a result, the equator's proximity hinders high mission performance in those cases [11, 12]. Unfortunately, the site location of a spaceport cannot be pinpointed by only considering the geographical factor.

As mentioned before, there are also other main factors that contributed to the D-M process. Safety and security are other serious factors in the point of decision process. Research published in 2019 revealed that spaceports should be located far enough from highly populated built-up areas, thereby reducing or eliminating the risk of damage and high mortality in case of a technical failure after launch. Additionally, flight trajectory planning poses an important challenge in the technical field that must be addressed. For a long time, research programs have been intensely supported by many governments to enhance state-owned space technologies because of their great benefits of achieving critical national security missions and increasing the military capabilities of countries. However, these advantages may sometimes deepen the conflicts between states. Therefore, flight trajectories should be planned not to cross an unfriendly country's territories [13].

To operate a spaceport smoothly also requires some basic features which provide operational and infrastructure services. Typically, these services are responsible for maintaining vital functions, including pre-flight preparations, the launch of a spacecraft, monitoring flights after launch, and tracking spacecraft in orbit. Besides the aforementioned operational services, assembly, integration, and testing of a space vehicle are also performed in these facilities [14]. A spaceport must also include different support facilities and infrastructures such as launch pads, liquid/solid/hybrid fuel tanks, landing pads, emergency response teams, runways, railways, roads, etc. [5]. These requirements clearly demonstrate that a reliable, simple, and low-cost transportation system is very important to maintain logistics support services for space operations. To achieve this, a spaceport should be built as close to an airport, port, railway station, or, if possible, several of them as possible.

The last critical factor is the stability of meteorological conditions and the possibility of natural disaster occurrence at the site location. It is odds-on that regions experiencing frequently either drastic changes in weather conditions or natural disasters such as earthquake, flood, and landslide should be excluded from the list of possible spaceport sites. The exclusion of the regions exhibiting unstable climate conditions can be reasoned that the success of a launch is heavily influenced by a change in prevailing wind direction and speed due to the varying weather condition. Consequently, a spaceport site selection can be made by taking into account the aforementioned main factors. Here, it is worth noting that depending on spaceports requirements, especially aimed to effectively conduct the promising business such as space tourism and space mining, some additional factors can be integrated into the D-M process for site selection.

This study aims to achieve another critical decision for a similar problem. The new D-M problem can be defined as follows: Several spaceports are located worldwide. One of the existing spaceports should be selected for launching a space vehicle of a country that does not possess its spaceport. Therefore, a new D-M process is needed to specify the most suitable spaceport according to some criteria. In this study, the required criteria are adapted from those researches developed to select a new spaceport site location.

Determining the appropriate spaceport is a multi-criteria decision-making problem. In other words, multiple criteria affect the decision-making process. Multi-criteria decision-making methods have been developed to solve such problems. In this study, the AHP method has been used to determine the criterion weights to be used in the selection of spaceports, and the TOPSIS method has been used to determine the selection order of the spaceports. A hybrid approach has been used to reach a better solution because the AHP method has a high consistency rate, and the TOPSIS method is based on the concept that the chosen alternative should be the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution.

The rest of this paper is arranged as follows. In Section 1.1, a literature review of spaceport selection articles has been presented. In Section 2, a detailed methodology is presented. In Section 3, a real-life spaceport selection application is explained and demonstrated how the proposed approach works. In Section 4, sensitivity analysis of the spaceport selection to be made considering the developing countries is given. Finally, in Section 5, the conclusion and discussion of this paper are presented.

1.1. Literature Review

In this section, a comparative discussion is given of the previous studies on the spaceport selection to highlight the contributions of the proposed study clearly. While mainly focusing on either a site selection for a new spaceport planned or amongst existing spaceports for a specific space mission, some of the previous studies are given in Table 1.

Table 1. The list of some previous studies on the spaceport site selection problem.

	Authors (Year)	Criteria	Selection Method
1	Cass and Schooff, (1999) [15]	Financing/Cost Infrastructure Shipping/Logistics Trajectory availability Range scheduling	Multi-Objective Value Analysis
2	Webber, (2004) [16]	Geographical/technical Site facilities Local infrastructure Space tourism specific Financial/admin Vehicle types	N/A
3	Nolek and Finger, (2009) [4]	Proximity to the equator Capacity of controlled access property Wide-range azimuth angle Military Protection Ongoing operations & maintenance costs Financial Models	N/A
4	Selvidge, (2010) [6]	Target user base Population density Latitude Climate Access Expansion and Site area Environmental impact Airspace Topography	N/A

5	Perwitasari, (2018) [17]	Location Technical requirement Safety and defence Economic land Social and culture Environment Spatial and land use	AHP Method
6	Rahma Diana et al., (2018) [5]	Potential market demand Projected economic impact	Descriptive-Analytic Method
7	Dachyar and Purnomo, (2018) [7]	Launch vehicles Type orbit Launch pad Transportation Infrastructure Population density Flight trajectory Weather Potential disaster Geographical location Tourism industry	AHP
8	This Study	Distance to Equator Main &Support Infrastructure Response Scheduling Flight Trajectory Population density Reliability Spaceport security Operation cost Transportation cost Meteorology Potential disaster	Hybrid PF AHP and PF TOPSIS

A feasibility study on some existing spaceports was conducted in order to evaluate their ability for achieving not only SLC-06 polar orbiting missions but also launches towards the east [15]. The alternatives were as follows: Kodiak Island Launch Complex, AK; Vandenberg AFB, CA; Kwajalein Missile Range, Republic of the Marshall Islands; Cape Canaveral AS, FL; Wallops Flight Facility, VA; Kourou, French Guiana; and Alcantara, Brazil. The qualities of the alternatives were evaluated by using a multi-objective value analysis in which the final value models of the alternative were compared. Each final value model was defined by a weighted sum of single dimensional value functions, individually obtained for each criterion. A single dimensional value function was obtained based on a scaled evaluation measure, enabling each alternative to be individually assessed with respect to each criterion. Prior to the comparison, a four-member team criticized all weights, measures and criteria. Having reached a consensus about the criteria and their weighted measures, a site survey was conducted. The survey results indicated that Kodiak and Wallops were more feasible than the others for the desired launch operations. However, the effects of the meteorological conditions were not considered in this multi-value analysis-based study. Moreover, the D-M method was not adapted to overcome the sensitivity against uncertainties and unknowns, capable of influencing the decision of experts deeply.

At the beginning of the 21st century, the recent technological developments open up a possibility for a new form of tourism activity called space tourism. However, commercial spaceports must meet some special needs to guarantee the sustainability of this new business. Therefore, it is crucial to investigate which spaceports around the world are preferable to investing in new building facilities required to meet the special needs. To address this issue, a comparative study in 2004 was made of the operated or planned spaceports [16]. First, the main features of a generic spaceports were given, considering the required infrastructures and services for space tourism. Then, some further information was also provided indicating the locations and capabilities of the existing spaceports such as the allowed launch azimuth angle range and mission types. Finally, it was suggested that Mojave, Baikonur, Kourou and Jiuquan spaceports were more capable for offering space tourism, according to the given data associated with the features and capabilities of the existing spaceports. Moreover, having conducted a research on the growth and forecasts about the space market, a framework for the business plan was also provided as a guideline when constructing a new commercial spaceport. Nevertheless, this decision process was not based on a structured selection method.

To determine the important capabilities needed for space tourism, a similar study was also performed but like [16], it did not also offer a D-M process for the selection of the most feasible between the existing spaceports [4]. The important factors associated with the technical, financial, political and schedule requirements, also given in the third row of Table 1, were determined for the traditional spaceports intending to branch out into the new space tourism business. In addition, the effects of these factors on facilitating the development of the new business model of the spaceports were examined. Along with the discussion on the disadvantages of the traditional spaceports to the space tourism, a new guideline was proposed to encourage investments in a successful public-private spaceport for this emerging tourism sector.

In recent decades, some researches were also carried out to evaluate the feasibility of the existing spaceports in a country for space tourism. In 2010, a site analysis was conducted to decide which cities in USA suitable as a site location to build a spaceport [6]. 20 cities in USA were selected from the 2008 Mastercard Worldwide Centers of Commerce Index and the list of the busiest airports in USA for 2007. The cities that were present on both lists were regarded as possible places for a spaceport offering services in the field of air and space travel. Then a set of criteria given in the fourth row of Table 1 was applied to evaluate the qualities of the selected cities. In the preliminary step, some cities were left out of the detailed D-M process due to the high population, the harsh weather conditions or the lack of areas large enough for construction. Accordingly, the elimination helped narrow down the number of the possible cities to two options, which were Atlanta and Dallas. Then, the suitable fields around Atlanta and Dallas were determined and analyzed by means of area maps, population statistics, climate charts, wind rose charts, soil maps, topographical maps, and airspace charts. According to the comparative results in terms of the predefined criteria, Atlanta was chosen as the most favorable. However, this decision process was not performed by using a structured technique unlike in the study presented here.

Unlike the developed countries, developing countries are keen to improve their capabilities in space operations or start their own space program. Therefore, to resolve the spaceport site selection problem also plays a very critical role in achieving these purposes. For example, researchers from Indonesia attempted to determine a spaceport location in Indonesia for promoting the development of the country's own space technology. In one of the previous studies [17], a D-M approach was proposed to select the most feasible location for building a new spaceport. Biak Island and Morotai Island in Indonesia were considered as two alternatives and the criteria used in the D-M process were listed as follows: spatial, technical requirement, location, safety and defense, economic, social and cultural environment. These criteria and their weightings were determined based on the opinions of the experts in the construction and the operations of a spaceport. Then, the selection was made by using a classical AHP method. According to the expert choice software, the primary factors were technical requirement and location, respectively. The result revealed that Biak Island was more suitable location for a new spaceport than Morotai Island. On the other hand, in these multi-criteria decision-making (MCDM) problems, unknowns and uncertainties were ignored.

To determine a feasible location for a new spaceport in Indonesia, a more detailed study including 4 alternatives and 12 accepted criteria covering different areas from tourism to infrastructure was also proposed [7]. Similarly, all the criteria and their weightings were determined based on the opinions of a team of experts in space technology in Indonesia. However, in contrast to [17], the primary factors were specified to be safety, and technical operations consisting of launch vehicle, launch pad and type of orbit. Then the weighted criteria were used to rank the alternatives and evaluate the feasibility of the alternatives in terms of their rankings. Like the previous study [17], Biak Island was also suggested to be the best location for building a new spaceport. In addition, the traditional AHP method was also applied to the D-M problem of interest without providing an effective tool to deal with the uncertainties and unknowns.

In another study, the effects of the spaceport site selection on economic efficiency and contributions to local economic development in Indonesia were investigated [5]. A statistical method, namely descriptive-analytic method, was evaluated in terms of potential market demand and projected economic impact by using the descriptive-analytic method. However, the decision was not made based on a structured approach to evaluate the economic effects of the spaceport site selection and the criteria considered were completely different from those in the proposed study.

In comparison to the previous studies mentioned above, a hybrid MCDM approach is proposed here to help experts decide which of the existing airports is feasible to launch satellites of Turkey for achieving specific missions. This proposed D-M approach is developed in the Pythagorean Fuzzy (PF) environment to eliminate the effects of the unknowns and uncertainties that may appear in the D-M process due to the inherent complexity of the problems of interest. Moreover, new criteria are also included into this proposed hybrid D-M approach. Reliability, response scheduling and potential disaster are introduced as the additional criteria and refer to the ratio of the successful launch number to the total launch number, the ability to provide flexible scheduling and the occurrence of natural disaster, respectively. Therefore, they are considered to be critical to a successful evaluation of the qualities of the existing spaceports.

2. METHODOLOGY

In this section, to provide a broad perspective to the reader, PF sets and MCDM methods used in the proposed approach for the selection of spaceports are reviewed. The methodology is examined under three subheadings: PF Sets Preliminaries, PF AHP, and PF TOPSIS.

2.1. Preliminaries for PF Sets

Intuitionistic fuzzy sets (IFS) are proposed by Atanassov [18] to express real-life problems better. These sets are explained with membership, non-membership, and hesitancy degrees. According to the IFS, the sum of membership and non-membership degrees cannot exceed 1. In some cases, in which squared sum of membership and non-membership degree is greater than 1, IFS is insufficient to explain uncertainty. Yager [19] proposed PFS to handle these situations. In these sets, the sum of membership and non-membership degrees can be greater than 1, but their squared sum cannot exceed 1. These sets are the generalization of IFS. The definitions of PFS are below.

Definition 1: Let a set X be a universe of discourse. A PF set P is an object having the form [20]:

$$P = \left\{\langle x, P\left(\mu_p(x), v_p(x)\right)\rangle \,|\, x \epsilon X\right\} \quad (1)$$

where the membership degree $\mu_p(x): x \mapsto [0,1]$ and non-membership degree $v_p(x): x \mapsto [0,1]$ of element $x\epsilon X$ to P. For every $x\epsilon X$, the following holds:

$$0 \leq \mu_p^2(x) + v_p^2(x) \leq 1 \quad (2)$$

Table 2. Comparison of IFS and PFS.

IFS		PFS	
μ	***v***	***μ***	***v***
0	1	0	1
0.1	0.9	0.1	0.99
0.2	0.8	0.2	0.98
0.3	0.7	0.3	0.95
0.4	0.6	0.4	0.92
0.5	0.5	0.5	0.87
0.6	0.4	0.6	0.8
0.7	0.3	0.7	0.71
0.8	0.2	0.8	0.6
0.9	0.1	0.9	0.44
1	0	1	0

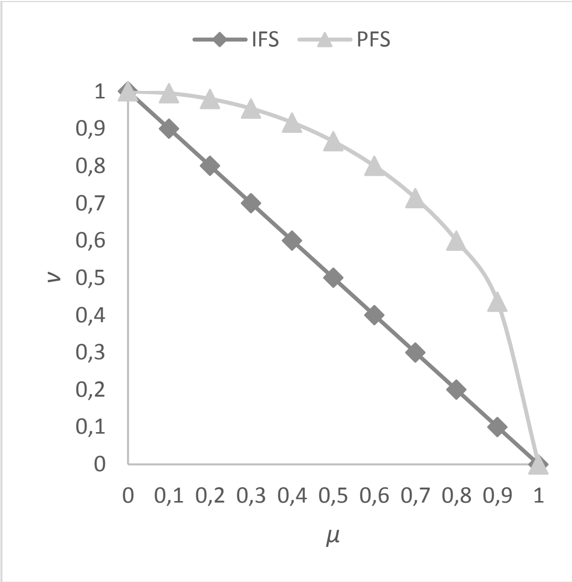

Figure 1. Graphical comparison of IFS and PFS.

The indeterminacy degree of x to P for any PFS P and $x\epsilon X$ $\pi_p(x)$ is defined as follows:

$$\pi_p(x) = \sqrt{1 - \mu_p^2(x) - v_p^2(x)} \quad (3)$$

Definition 2: If $\beta_1 = P(\mu_{\beta 1}, v_{\beta 1})$ and $\beta_2 = P(\mu_{\beta 2}, v_{\beta 2})$ are the PF numbers, $\lambda > 0$, the mathematical operations on β_1 and β_2 are defined as follows [20, 21]:

$$\beta_1 \oplus \beta_2 = P\left(\sqrt{\mu_{\beta 1}^2 + \mu_{\beta 2}^2 - \mu_{\beta 1}^2\mu_{\beta 2}^2}, v_{\beta 1}v_{\beta 2}\right) \quad (4)$$

$$\beta_1 \otimes \beta_2 = P\left(\mu_{\beta 1}\mu_{\beta 2}, \sqrt{v_{\beta 1}^2 + v_{\beta 2}^2 - v_{\beta 1}^2 v_{\beta 2}^2}\right) \quad (5)$$

$$\lambda\beta_1 = P\left(\sqrt{1 - \left(1 - \mu_{\beta 1}^2\right)^{\lambda}}, v_{\beta 1}^{\lambda}\right) \quad (6)$$

$$\beta_1^{\lambda} = P\left(\mu_{\beta 1}^{\lambda}, \sqrt{1 - \left(1 - v_{\beta 1}^2\right)^{\lambda}}\right) \quad (7)$$

Definition 3: The distance between two PFS is defined by Zhang and Xu [20] as shown in Eq. (8):

$$d(\beta_1, \beta_2) = \frac{1}{2}\left(\left|\mu_{\beta 1}^2 - \mu_{\beta 2}^2\right| + \left|v_{\beta 1}^2 - v_{\beta 2}^2\right| + \left|\pi_{\beta 1}^2 - \pi_{\beta 2}^2\right|\right) \quad (8)$$

Definition 4: If more than one DM evaluates the criteria, the interval-valued PF numbers are aggregated using the interval-valued PF weighted geometric (IVPFWG) operator $\beta_i = ([\mu_i{}^L, \mu_i{}^U], [v_i{}^L, v_i{}^U])$is a PF number. Where n is the number of DM, and $w_j = (w_1, w_2, \ldots, w_n)^T$ be the weight vector of $\beta_i (i = 1, 2, \ldots, n)$ with $\sum_{i=1}^{n} w_i = 1$, then an IVPFWG operator is shown as Eq. (9) [22].

$$IVPFWG(\beta_1, \beta_2, \ldots, \beta_n) = \left(\left[\prod_{j=1}^{n}\left(\mu_{\alpha_j}^L\right)^{w_j}, \prod_{j=1}^{n}\left(\mu_{\alpha_j}^U\right)^{w_j}\right], \left[\prod_{j=1}^{n}\left(v_{\alpha_j}^L\right)^{w_j}, \prod_{j=1}^{n}\left(v_{\alpha_j}^U\right)^{w_j}\right]\right) \quad (9)$$

2.2. PF AHP

AHP is an MCDM method developed by Saaty [23]. AHP is a method that can evaluate qualitative and quantitative variables together, taking into account the priorities of the group or individual in D-M problems. AHP method has been first extended by Ilbahar et al. [24] in the PF environment. The steps of the PF AHP method are as follows.

Step 1. Structure the compromised pairwise matrix $A = (a_{ik})_{m\times m}$ on nine points of linguistic evaluation by DM using the scale proposed by Ilbahar [24] in Table 3.

Table 3. Weighting scale for the interval-valued PF AHP method.

Linguistic Terms	Interval-valued PF numbers			
	μ_L	μ_U	v_L	v_U
Extremely Low / S1	0	0	0.9	1
Very Low / S2	0.1	0.2	0.8	0.9
Low / S3	0.2	0.35	0.65	0.8
Below Average / S4	0.35	0.45	0.55	0.65
Average / S5	0.45	0.55	0.45	0.55
Above Average / S6	0.55	0.65	0.35	0.45
High / S7	0.65	0.8	0.2	0.35
Very High / S8	0.8	0.9	0.1	0.2
Extremely High/ S9	0.9	1	0	0
Exactly Equal / S10	0.196	0.196	0.196	0.19

Step 2. Calculate the difference matrices $D = (d_{ik})_{m\times m}$ between lower and upper values of the membership and non-membership functions by using Eq. (10) and Eq. (11):

$$d_{ik_L} = \mu_{ik_L}^2 - v_{ik_U}^2 \quad (10)$$

$$d_{ik_U} = \mu_{ik_U}^2 - v_{ik_L}^2 \quad (11)$$

Step 3. Calculate the interval multiplicative matrix $S = (S_{ik})_{m\times m}$ by using Eq. (12) and Eq. (13):

$$S_{ik_L} = \sqrt{1000^{d_L}} \quad (12)$$

$$S_{ik_U} = \sqrt{1000^{d_U}} \quad (13)$$

Step 4. Calculate the determinacy value $(\tau_{ik})_{m\times m}$ by using Eq. (14):

$$\tau_{ik} = 1 - (\mu_{ik_U}^2 - \mu_{ik_L}^2) - (v_{ik_U}^2 - v_{ik_L}^2) \quad (14)$$

Step 5. The determinacy values are multiplied with Interval multiplicative matrix for obtaining the matrix of weights, $T = (t_{ik})_{m\times m}$ before normalization using Eq. (15):

$$t_{ik} = \left(\frac{S_{ik_L} + S_{ik_U}}{2}\right) \times \tau_{ik} \quad (15)$$

Step 6. Calculate the normalized priority weight w_i by using Eq. (16):

$$w_i = \frac{\sum_{k=1}^{m} t_{ik}}{\sum_{i=1}^{m}\sum_{k=1}^{m} t_{ik}} \quad (16)$$

2.3. PF TOPSIS

TOPSIS is an MCDM method developed by Hwang and Yoon [25]. The TOPSIS method is based on choosing the alternative closest to the Positive Ideal Solution and the furthest to the Negative Ideal Solution. Cevik Onar et al. [26] extended the TOPSIS method for the first time in the PF environment. The steps of the PF TOPSIS method are as follows.

Step 1. Construct decision matrix $R = \left(C_j(x_i)\right)_{m\times n}$ based on PF numbers. $C_j(j = 1,2,\ldots,n)$ and $x_i(i = 1,2,\ldots,m)$ show to values of criteria and alternatives.

$$R = \left(C_j(x_i)\right)_{m\times n} = \begin{array}{c} \\ x_1 \\ \vdots \\ x_m \end{array} \begin{array}{c} C_1 \quad \cdots \quad C_n \\ \begin{bmatrix} P(u_{11}, v_{11}) & \cdots & P(u_{1n}, v_{1n}) \\ \vdots & \ddots & \vdots \\ P(u_{m1}, v_{m1}) & \cdots & P(u_{nm}, v_{nm}) \end{bmatrix} \end{array} \quad (17)$$

Step 2. Calculate the PF Positive Ideal Solution (PIS) by using Eq. (18), and Negative Ideal Solution (NIS) by using Eq. (19):

$$x^+ = \left\{C_j, \max_i \langle s\left(C_j(x_i)\right)\rangle \mid j = 1,2,\ldots,n\right\} = \{\langle C_1, P(u_1^+, v_1^+)\rangle, \langle C_2, P(u_2^+, v_2^+)\rangle, \ldots, \langle C_n, P(u_n^+, v_n^+)\rangle\} \quad (18)$$

$$x^- = \left\{C_j, \min_i \langle s\left(C_j(x_i)\right)\rangle \mid j = 1,2,\ldots,n\right\} = \{\langle C_1, P(u_1^-, v_1^-)\rangle, \langle C_2, P(u_2^-, v_2^-)\rangle, \ldots, \langle C_n, P(u_n^-, v_n^-)\rangle\} \quad (19)$$

Table 4. Performance rating scale of alternatives proposed by Pérez-Domínguez et al. [27].

Linguistic Terms	Interval-valued PF	
	U	V
Extremely Bad / G1	0.1	0.99
Very Bad / G2	0.1	0.97
Bad / G3	0.25	0.92
Middle Bad / G4	0.4	0.87
Middle / G5	0.5	0.8
Middle Good / G6	0.6	0.71
Good / G7	0.7	0.6
Very Good / G8	0.8	0.44
Extremely Good / G9	1	0

Step 3. Calculate the distance from *PIS* and *NIS* by using Eq. (20) and Eq. (21):

$$D(x_i, x^+) = \sum_{j=1}^{n} w_j d\left(C_j(x_i), C_j(x^+)\right) \quad (20)$$
$$= \frac{1}{2}\sum_{j=1}^{n} w_j \left(\begin{array}{c} \left|(\mu_{ij})^2 - (\mu_j^+)^2\right| \\ + \left|(v_{ij})^2 - (v_j^+)^2\right| + \left|(\pi_{ij})^2 - (\pi_j^+)^2\right| \end{array} \right)$$

$$D(x_i, x^-) = \sum_{j=1}^{n} w_j d\left(C_j(x_i), C_j(x^-)\right)$$
$$= \frac{1}{2}\sum_{j=1}^{n} w_j \begin{pmatrix} \left|(\mu_{ij})^2 - (\mu_j^-)^2\right| \\ + \left|(v_{ij})^2 - (v_j^-)^2\right| + \left|(\pi_{ij})^2 - (\pi_j^-)^2\right| \end{pmatrix} \quad (21)$$

Step 4. Option 1. Calculate the relative closeness $RC(x_i)$ of the alternative x_i by using Eq. (22):

$$RC(x_i) = \frac{D(x_i, x^-)}{\left(D(x_i, x^+) + D(x_i, x^-)\right)} \quad (22)$$

Step 4. Option 2. Hadi-Vencheh and Mirjaberi [28] proposed another RC coefficient $\xi(x_i)$ Eq. (23):

$$\xi(x_i) = \frac{D(x_i, x^-)}{D_{max}(x_i, x^-)} - \frac{D(x_i, x^+)}{D_{min}(x_i, x^+)} \quad (23)$$

3. REAL-LIFE APPLICATION

To demonstrate the proposed approach's applicability, a spaceport selection case for Turkey's next-generation satellites, which will launch, was studied.

In December 2018 Turkey Space Agency was established to make the applications required medium and long-term goals for space and aviation science, basic principles and approaches, goals and priorities, performance criteria. However, starting of space technology in Turkey is based on 1994. Turkey has launched satellite TURKSAT 1A from the Guiana Space Center for the first time on 24 December 1994. However, it fell into the ocean after 12 minutes due to errors in the launcher. Shortly after that, TURKSAT 1B was successfully launched from the Guiana Space Center. After those launches, a new adventure began for Turkey. TURKSAT 1C in 1996 and TURKSAT 2A in 2001 were launched from Guiana Space Center. No satellite was launched until the TURKSAT 3A was launched in 2008. RASAT from Yasny Launch Base in 2011, GOKTURK-2 from Jiuquan Satellite Launch Center in 2012, TURKSAT 3USAT from Jiuquan Satellite Launch Center in 2013, TURKSAT 4A from Baikonur Cosmodrome in 2014, and TURKSAT 4B from Baikonur Cosmodrome in 2015 was launched. Planned to be launched in 2009 but could not be launched due to Israel's impact on the launching company, GOKTURK 1 was launched from the Guiana Space Center in 2016. Finally, in January 2021, TURKSAT 5A was launched from Cape Canaveral Space Center. As shown in Table 5, Turkey has six active satellites. Three of these are satellites for communication purposes and three for observation purposes. There are three more satellites planned to be launched in the next two years. Among these, TURKSAT 6A and IMECE are the first satellites built with domestic facilities. Moreover, Turkey Micro Satellite Launch System, which contracts were made in 2018, will be operational in the years ahead. This study was carried out to determine from which spaceport the satellites to be launched until the Micro-Satellite Launch System becomes working.

Table 5. Turkey's launched satellites from 1994 to today.

	Date	**Satellite**	**Spaceport**	**Situation**
1	24 January 1994	TURKSAT 1A	Guiana Space Center	Inactive
2	10 August 1994	TURKSAT 1B	Guiana Space Center	Inactive
3	10 July 1996	TURKSAT 1C	Guiana Space Center	Inactive
4	11 January 2001	TURKSAT 2A	Guiana Space Center	Inactive
5	13 June 2008	TURKSAT 3A	Guiana Space Center	Active
6	17 August 2011	RASAT	Yasny Launch Base	Active
7	18 December 2012	GOKTURK 2	Jiuquan Satellite Launch Center	Active
8	26 April 2013	TURKSAT 3USAT	Jiuquan Satellite Launch Center	Inactive
9	14 February 2014	TURKSAT 4A	Baikonur Cosmodrome	Active
10	16 October 2015	TURKSAT 4B	Baikonur Cosmodrome	Active
11	5 December 2016	GOKTURK 1	Guiana Space Center	Active
12	8 January 2021	TURKSAT 5A	Cape Canaveral Space Center	Launched
13	2021	TURKSAT 5B	Cape Canaveral Space Center	Planned
14	2022	TURKSAT 6A	-	Planned
15	2022	IMECE	-	Planned

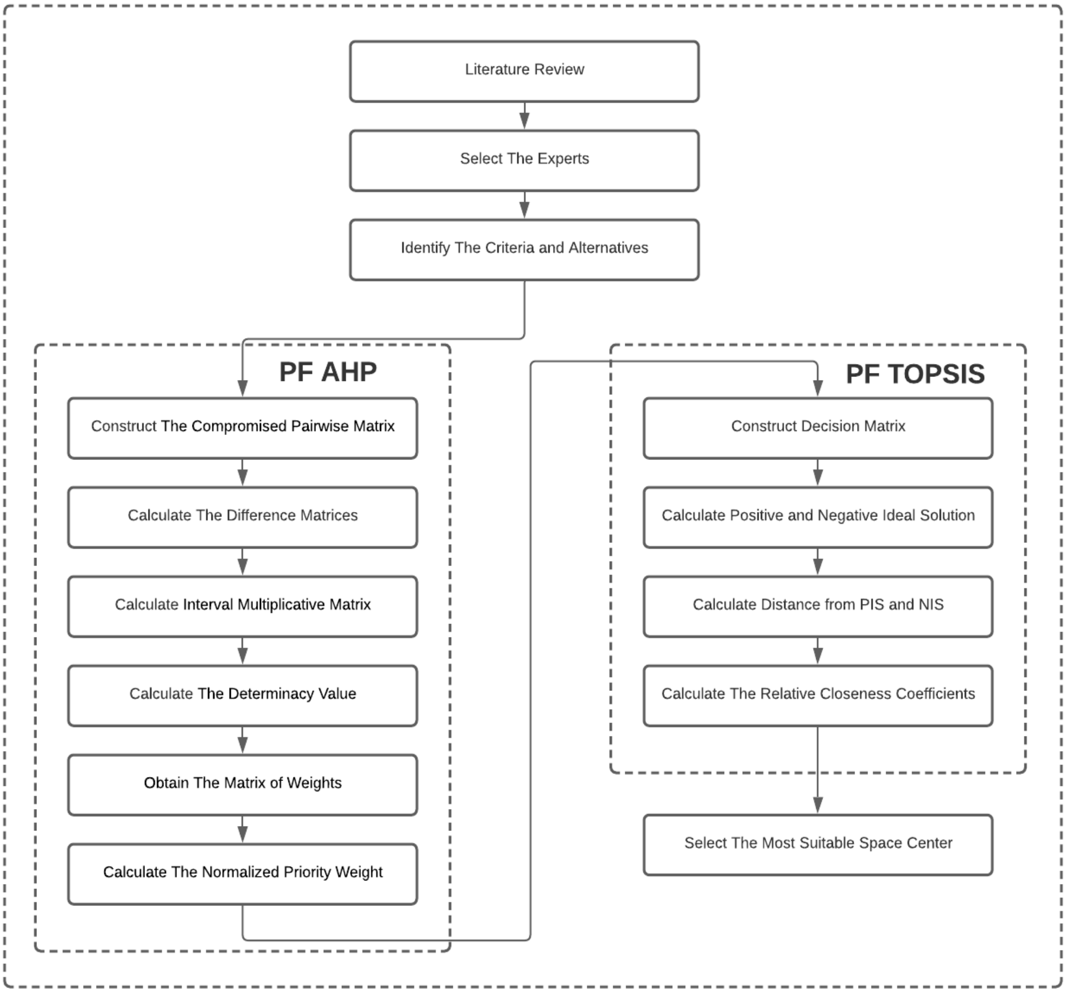

Figure 2. Framework of the proposed approach.

In this direction, the framework of the approach to be proposed has been determined as shown in Fig. 2. According to the proposed approach, the criteria weights were calculated with PF AHP, and the ranking of the alternatives was made with PF TOPSIS. Three faculty members of Necmettin Erbakan University, Faculty of Aeronautics and Astronautics, Department of Space and Satellite Engineering, experts in space and satellites, were selected to determine which criteria are effective for evaluating the spaceports to be used for launching satellites. One of the selected experts in space and satellite has the title of associate professor, and two of them have the title of assistant professor. Experts have been actively teaching students as faculty members for a minimum of three years, starting from the end of their doctorate. Two of the experts have a bachelor's degree in mechanical engineering, and one of them has a bachelor's degree in physics. In addition, experts contribute to the literature with their studies in the field of satellite engineering. As a result of the evaluations made, 11 most effective criteria were determined under five main criteria to select the most suitable spaceport for launching a satellite. These criteria (as shown in Fig. 3) are explained in Table 6.

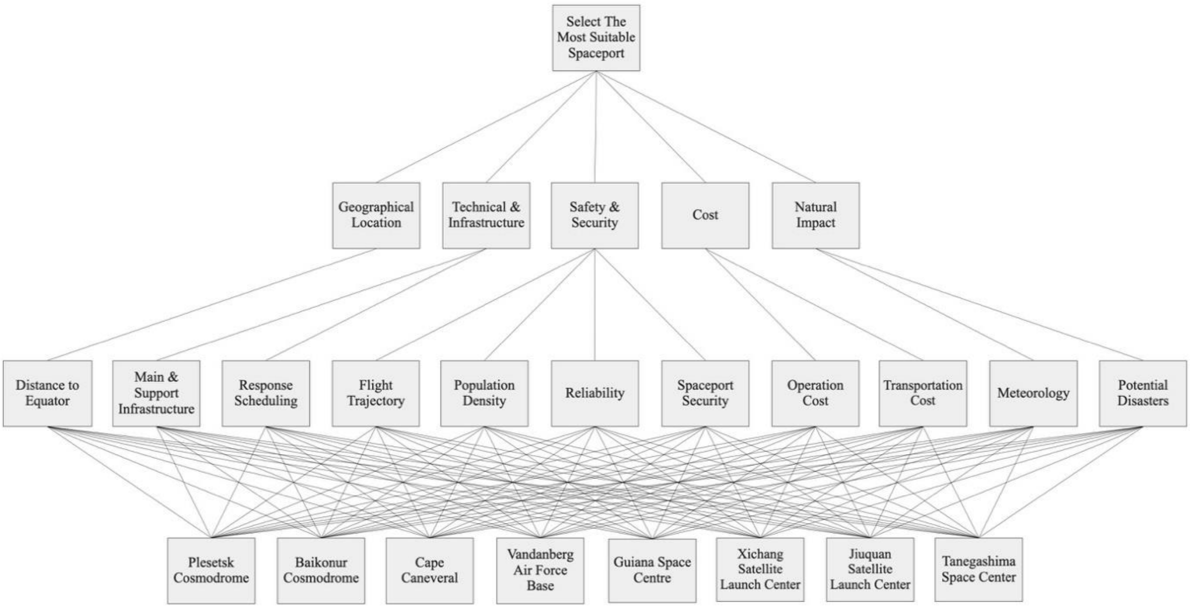

Figure 3. Hierarchical structure of the problem.

Table 6. Spaceport Selection Criteria.

	Criteria	**Explanation**
Cr_1	Distance to the Equator	The distance to the equator. As the length to the Equator decreases, the power required to launch will fall, and useful load carrying capacity becomes high. The spaceport with a low distance to the Equator is more likely to be selected.
Cr_2	Main & Support Infrastructure	It shows how much space the spaceport has and how many launch pads it has. The being selected ratio of a spaceport that has high main & support infrastructure is more.
Cr_3	Response Scheduling	Flexible scheduling for the canceled launch when any problem is encountered. The spaceport's response scheduling, which has a low launching busy, is higher, and the being selected ratio is also higher.
Cr_4	Flight Trajectory	The azimuth angle required for launching a satellite without violating the countries' air borders that we are not allies with. The being selected ratio of a spaceport that has a high flight trajectory is more.
Cr_5	Population Density	Human settlement in the surrounding area where the spaceport is located. The being selected ratio of a spaceport that has a low population density is more.
Cr_6	Reliability	The successful launch ratio of the spaceport. The being selected rate of a spaceport that has high reliability is more.
Cr_7	Spaceport Security	It is the security level of the spaceport. The being selected ratio of a spaceport that has high spaceport security is more.
Cr_8	Operation Cost	It is the total cost of all operations performed in the spaceport. The being selected ratio of a spaceport that has a low operation cost is more.
Cr_9	Transportation Cost	Transportation costs depending on the distance to the spaceport. The further the country to launch the satellite is from the spaceport, the higher the transportation cost. In this direction, the rate of being selected the spaceport with high transportation costs is lower.
Cr_{10}	Meteorology	It represents the meteorology based on wind and precipitation rates in the spaceport area. The spaceport with a low meteorology rate is more likely to be selected.
Cr_{11}	Potential Disasters	Natural disasters that can occur in the area where the spaceport is located. The spaceport with a low potential disasters ratio is more likely to be selected.

After the criteria are determined, the first step of the approach, using the AHP method in the PF environment, is to calculate the criterion weights.

As the first step in the PF AHP method, paired comparison matrices are created by experts for each criterion with linguistic variables, as shown in Table 7-9.

Table 7. Pairwise comparison matrix of Expert 1.

	Cr_1	Cr_2	Cr_3	Cr_4	Cr_5	Cr_6	Cr_7	Cr_8	Cr_9	Cr_{10}	Cr_{11}
Cr_1	S10	S6	S7	S5	S5	S7	S8	S6	S6	S6	S7
Cr_2	S4	S10	S7	S4	S4	S6	S7	S6	S6	S6	S7
Cr_3	S3	S3	S10	S3	S3	S4	S6	S4	S4	S4	S6
Cr_4	S5	S6	S7	S10	S5	S7	S8	S6	S6	S6	S7
Cr_5	S5	S6	S7	S5	S10	S7	S8	S6	S6	S6	S7
Cr_6	S3	S4	S6	S3	S3	S10	S6	S4	S4	S4	S6
Cr_7	S2	S3	S4	S2	S2	S4	S10	S3	S3	S3	S4
Cr_8	S4	S4	S6	S4	S4	S6	S7	S10	S5	S4	S6
Cr_9	S4	S4	S6	S4	S4	S6	S7	S5	S10	S4	S6
Cr_{10}	S4	S4	S6	S4	S4	S6	S7	S6	S6	S10	S7
Cr_{11}	S3	S3	S4	S3	S3	S4	S6	S4	S4	S3	S10

Table 8. Pairwise comparison matrix of Expert 2.

	Cr_1	Cr_2	Cr_3	Cr_4	Cr_5	Cr_6	Cr_7	Cr_8	Cr_9	Cr_{10}	Cr_{11}
Cr_1	S10	S7	S7	S6	S6	S7	S8	S6	S6	S6	S8
Cr_2	S3	S10	S4	S4	S4	S6	S7	S4	S4	S4	S6
Cr_3	S3	S4	S10	S3	S3	S4	S6	S4	S4	S3	S6
Cr_4	S4	S6	S7	S10	S6	S7	S8	S6	S6	S6	S7
Cr_5	S4	S6	S7	S4	S10	S6	S7	S6	S6	S5	S7
Cr_6	S3	S4	S6	S3	S4	S10	S6	S4	S4	S4	S6
Cr_7	S2	S3	S4	S2	S3	S4	S10	S3	S3	S3	S4
Cr_8	S4	S6	S6	S4	S4	S6	S7	S10	S6	S4	S7
Cr_9	S4	S6	S6	S4	S4	S6	S7	S5	S10	S4	S7
Cr_{10}	S4	S6	S7	S4	S5	S6	S7	S6	S6	S10	S7
Cr_{11}	S2	S4	S4	S3	S3	S4	S6	S3	S3	S3	S10

Table 9. Pairwise comparison matrix of Expert 3.

	Cr_1	Cr_2	Cr_3	Cr_4	Cr_5	Cr_6	Cr_7	Cr_8	Cr_9	Cr_{10}	Cr_{11}
Cr_1	S10	S6	S8	S6	S6	S6	S8	S7	S7	S7	S8
Cr_2	S4	S10	S7	S4	S4	S4	S7	S6	S6	S6	S7

Cr_3	S2	S3	S10	S3	S3	S3	S6	S4	S4	S4	S6
Cr_4	S4	S6	S7	S10	S5	S4	S8	S6	S7	S6	S7
Cr_5	S4	S6	S7	S5	S10	S4	S8	S6	S7	S6	S7
Cr_6	S4	S6	S7	S6	S6	S10	S8	S7	S7	S6	S8
Cr_7	S2	S3	S4	S2	S2	S2	S10	S3	S4	S3	S4
Cr_8	S3	S4	S6	S4	S4	S3	S7	S10	S6	S4	S6
Cr_9	S3	S4	S6	S3	S3	S3	S6	S4	S10	S4	S6
Cr_{10}	S3	S4	S6	S4	S4	S4	S7	S6	S6	S10	S7
Cr_{11}	S2	S3	S4	S3	S3	S2	S6	S4	S4	S3	S10

Linguistic pairwise comparison matrices evaluated by DM are shown in the tables above. The linguistic variables in these tables have been converted to PF numbers. The aggregated comparison matrix was obtained by using the IVPFWG operator because of more than one DM. As an example, the IVPFWG between Cr_1 and Cr_2 is calculated using Eq. (9) as follows:

$$Cr_1 - Cr_2 = \sqrt[3]{\begin{array}{c}(0.550\ 0.650\ 0.350\ 0.450) * \\ (0.650\ 0.800\ 0.200\ 0.350) * (0.550\ 0.650\ 0.350\ 0.450)\end{array}}$$

$$= \sqrt[3]{(0.197\ 0.338\ 0.025\ 0.071)} = (0.581\ 0.697\ 0.290\ 0.414) \quad (24)$$

Now that the aggregated pairwise matrix is created with PF numbers, Step 1 has been applied, and we can proceed with the other steps. After this step, the calculations will be shown via *Cr_1* and *Cr_2* as an example. In step 2, the difference matrices between lower and upper values of the membership and non-membership functions were calculated as follows:

$$d_{Cr1,Cr2_L} = 0.581^2 - 0.414^2 = 0.167 \quad (25)$$

$$d_{Cr1,Cr2_U} = 0.697^2 - 0.290^2 = 0.401 \quad (26)$$

In Step 3, the interval multiplicative matrix was calculated as follows:

$$s_{Cr1,Cr2_L} = \sqrt{1000^{0.167}} = 1.780 \quad (27)$$

$$s_{Cr1,Cr2_U} = \sqrt{1000^{0.401}} = 3.993 \quad (28)$$

In Step 4, the determinacy value was calculated as follows:

$$\tau_{Cr1,Cr2_L} = 1 - (0.697^2 - 0.581^2) - (0.414^2 - 0.290^2) = 0.766 \quad (29)$$

In Step 5, the weight of *Cr_1* was calculated as follows:

$$T_{Cr1,Cr2_L} = \left(\frac{1.780 + 3.993}{2}\right) * 0.766 = 2.211 \quad (30)$$

(31)

$$Total\ T_{Cr1} = 1 + 2.211 + \cdots + 6.965 = 37.030 \quad (32)$$

$$w_{Cr1} = \frac{37.030}{175.044} = 0.212$$

The results in Table 10 have been obtained by calculating the weights of each criterion.

Table 10. Weights of criteria for spaceport selection according to PF AHP.

	w_i	**Rank**
Cr_1	0.212	1
Cr_2	0.085	5
Cr_3	0.037	9
Cr_4	0.164	2
Cr_5	0.143	3
Cr_6	0.078	6
Cr_7	0.018	11
Cr_8	0.074	7
Cr_9	0.064	8
Cr_{10}	0.098	4
Cr_{11}	0.027	10

Now that the weights are calculated with PF AHP, we can move on to the second part of the proposed approach to compare the alternative spaceports with PF TOPSIS. As a first step, alternative spaceports are evaluated according to the linguistic performance scale in Table 4 against the specified criteria. Then, the decision matrix is created with the PF values corresponding to the linguistic expressions. Although three decision-makers made the spaceport assessment, the decision matrix shown in Table 11 was formed by consensus of the three.

Along with Step 1, the next steps calculations will be shown via *Plesetsk Cosmodrome* and Cr_1 as an example. The score of *Plesetsk Cosmodrome* concerning the criterion C_1 is obtained as follows:

$$Score_{Plesetsk\ Cosmodrome,C1} = 0.100^2 - 0.970^2 = -0.931 \quad (33)$$

The degree of indeterminacy of *Plesetsk Cosmodrome* with respect to the Cr_1 criterion is calculated based on Eq. (3) as follows:

$$\pi_{Plesetsk\ Cosmodrome,Cr1} = 1 - \sqrt{0.100^2 - 0.970^2} = 0.222 \quad (34)$$

In Step 2, the *PIS* and *NIS* of Cr_1 criterion is calculated as follows:

$$x^{+}_{Cr1} = \max\begin{Bmatrix} (-0.931)\ (-0.597)\ 0.130\ (-0.144) \\ 1.000\ 0.130\ (-0.390)\ (-0.144) \end{Bmatrix} = 1.000 \quad (35)$$

$$x^{-}_{Cr1} = \min\begin{Bmatrix} (-0.931)\ (-0.597)\ 0.130\ (-0.144) \\ 1.000\ 0.130\ (-0.390)\ (-0.144) \end{Bmatrix} = -0.931 \quad (36)$$

Table 11. Rating alternatives according to the criteria by experts.

	Cr_1	Cr_2	Cr_3	Cr_4	Cr_5	Cr_6	Cr_7	Cr_8	Cr_9	Cr_{10}	Cr_{11}
Plesetsk	G2	G7	G7	G6	G8	G8	G4	G8	G8	G8	G7
Baikonur	G4	G8	G7	G4	G7	G8	G4	G8	G8	G5	G7
Cape Canaveral	G7	G7	G4	G5	G9	G4	G8	G4	G3	G4	G7
Vandenberg	G6	G5	G8	G6	G7	G5	G8	G4	G2	G5	G7
Guiana	G9	G5	G7	G1	G8	G8	G8	G2	G4	G5	G5
Xichang	G7	G6	G5	G1	G1	G8	G6	G8	G5	G6	G6
Jiuquan	G5	G5	G7	G1	G1	G9	G6	G8	G6	G7	G6
Tanegashima	G6	G4	G8	G9	G7	G4	G9	G6	G4	G2	G4

In Step 3, the distance between the *PIS* and the *Plesetsk Cosmodrome* concerning the criterion Cr_1 is obtained as follows:

$$D^{+}(x_{Plesetsk\ Cosmodrome}, x^{+}_{Cr1})_{Cr1} = |0.100^2 - 1.000^2| + |0.970^2 - 0^2| + |0.222^2 - 0^2| = 1.980 \quad (37)$$

The distance between the *NIS* and the *Plesetsk Cosmodrome* concerning the criterion Cr_1 is obtained as follows:

$$D^{-}(x_{Plesetsk\ Cosmodrome}, x^{-}_{Cr1})_{Cr1} = |0.100^2 - 0.100^2| + |0.970^2 - 0.970^2| + |0.222^2 - 0.222^2| = 0 \quad (38)$$

The total distance to the *PIS* is obtained as follows:

$$D^{+}(x_{Plesetsk\ Cosmodrome}, x^{+}) = \frac{1}{2} * \big((0.212 * 1.980) + (0.085 * 0.333) + \cdots + (0.027 * 0)\big) = 0.429 \quad (39)$$

The total distance to the *NIS* is obtained as follows:

$$D^{-}(x_{Plesetsk\ Cosmodrome}, x^{-}) = \frac{1}{2} * \big((0.212 * 0) + (0.085 * 0.794) + \cdots + (0.027 * 0.794)\big) = 0.471 \quad (40)$$

In Step 4, the *RC* of *Plesetsk Cosmodrome* is obtained by using Eq. (41) as follows:

$$RC(x_{Plesetsk\ Cosmodrome}) = \frac{0.471}{0.471 + 0.429} = 0.523 \quad (41)$$

Option 2 of Step 4, that is Hadi - Vencheh and Mirjaberi's *RC* of *Plesetsk Cosmodrome* is obtained by using Eq. (42) as follows:

$$\zeta(x_{Plesetsk\ Cosmodrome}) = \frac{0.471}{0.471} - \frac{0.429}{0.429} = 0 \quad (42)$$

As a result of the operations performed in the Step 4 and the option 2 of the 4th step, each alternative spaceport score was calculated. Score calculations of alternative spaceports have been made as shown in Table 12.

Table 12. Scores and ranking orders of alternatives.

	RC	Rank	Hadi Vencheh	Rank
Plesetsk	0.523	1	0.000	1
Baikonur	0.463	5	-0.241	5
Cape Canaveral	0.464	4	-0.235	4
Vandenberg	0.398	6	-0.509	6
Guiana	0.505	2	-0.070	2
Xichang	0.366	7	-0.616	7
Jiuquan	0.354	8	-0.652	8
Tanegashima	0.477	3	-0.183	3

4. SENSITIVITY ANALYSIS

In this section, sensitivity analysis has been performed to meet the special needs of developing countries with limited budgets to launch satellites but are looking for spaceports with fast launch planning and quality infrastructure.

Experts were consulted on which criteria to evaluate spaceports have more importance in developing countries with such special requests. As a result of the consultations, it was decided that developing countries may give more importance to the following four criteria than others: i) Main & Support infrastructure, ii) Response scheduling, iii) Operation cost, and iv) Transportation cost.

The effect of using different ratios of criteria weights affecting the selection of spaceport in developing countries on the selection process was investigated with scenario analysis by the authors. As the weights of the criteria determined as a result of the analyzes (shown in Table 13) increase, the order of selection of alternative spaceports changes as shown in Figure 5. But Plesetsk Cosmodrome is still the most suitable spaceport for developing countries.

Table 13. Spaceport selection weights according to the increase in criterion weights.

	Current State	%10 Increase	%30 Increase	%50 Increase	%70 Increase	%100 Increase
Plesetsk	14.74	14.93	15.31	15.70	16.10	16.72
Baikonur	13.04	13.34	13.96	14.59	15.23	16.21
Cape Canaveral	13.07	12.89	12.52	12.15	11.78	11.20
Vandenberg	11.21	11.06	10.74	10.41	10.09	9.58
Guiana	14.23	13.94	13.35	12.76	12.15	11.22
Xichang	10.31	10.42	10.65	10.88	11.11	11.47
Jiuquan	9.97	10.13	10.45	10.78	11.11	11.61
Tanegashima	13.44	13.30	13.01	12.73	12.43	11.99

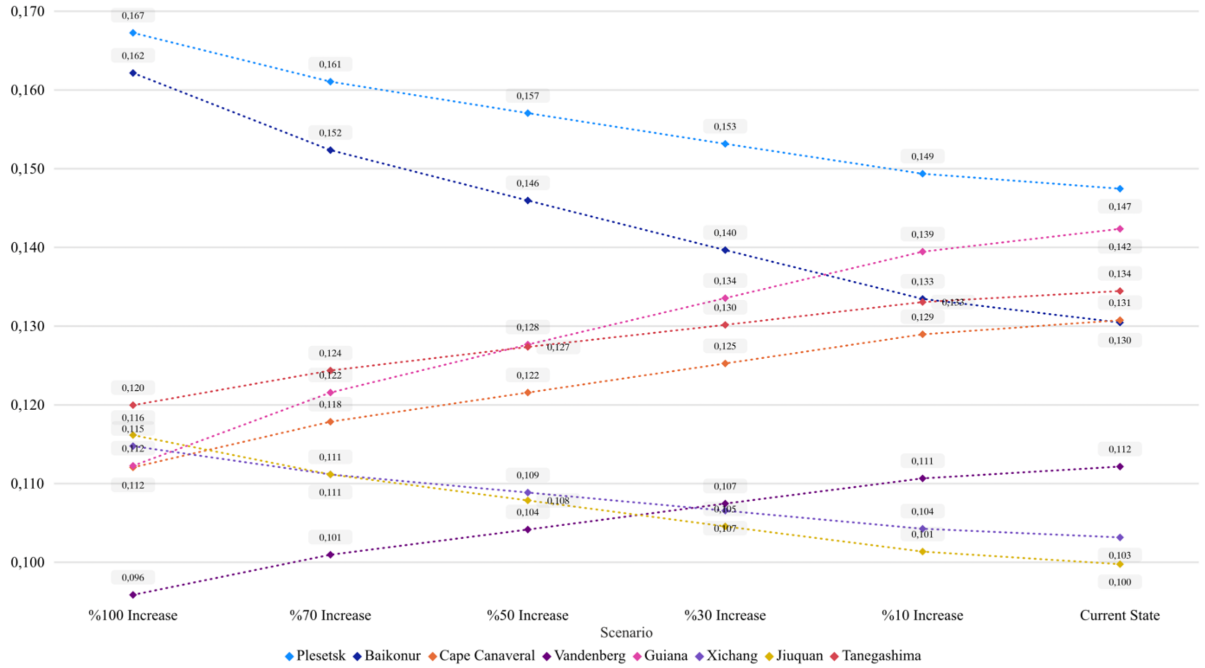

Figure 4. Spaceport selection weights according to the increase in criterion weights.

5. CONCLUSION

The effects of the space age, which started with the launching of Sputnik 1 in 1957, have emerged as satellites that countries need for observation and communication purposes. Thoughts about manned exploration studies and colonization on Mars, which will be made in the years that were not considered to be very future, have started to be spoken a lot. Studies have been initiated by different countries and private companies so that these thoughts do not remain only as thoughts. Turkey's space age began with the launching in 1994 TURKSAT 1A. A total of 12 satellites have been launched so far, the last being on January 8, 2021. Three more satellites are planned to be launched by the end of 2022. Besides, the space work to do the next ten years has been declared by Turkey Space Agency, established in 2018. Within this ten-year program, it was reported that the Micro Satellite Launch System, whose agreements were concluded in 2018, will be ready for use in the coming years. However, the satellites that will be launched until this time will be launched using different spaceports. It has been conclusively shown that Turkey will increase space science studies in the next year. Until today, 12 satellites belonging to Turkey have launched from five different spaceports. Questions have been raised about until the Micro Satellite Launch System is active, which spaceport will be used.

In this study, the decision was determined from which spaceport the satellites planned to be ready belonging to Turkey would be launched, ignoring political and diplomatic relations. Since multiple criteria affect selecting the spaceport, the spaceport selection has been made using MCDM methods. The approach was proposed in the PF environment to eliminate the uncertainties in the D-M process due to the high accuracy rate in expressing real-life problems. The criterion weights that affect the spaceport selection were computed based on the AHP method in the approach. The ranking of the alternative spaceports was made based on the TOPSIS method. Previous studies have failed to consider all the possible criteria that affect the spaceport selection problem. The study's results show Plesetsk Cosmodrome was chosen as the most suitable spaceport when political and diplomatic relations to be ignored for Turkey. This study is not only valid for a single country but also adaptable to different countries. It is possible that in further research, other MCDM methods or different fuzzy environments may be used. Also, different results can be yielded by adding political and diplomatic relations in further study.

6. REFERENCES

[1] ESA Space Debris Office, “ESA’s Annual Space Environment Report,” *ESA Space Debris Office*, 2019, [Online]. Available: https://www.sdo.esoc.esa.int. [Accessed: 7-Jun-2021].

[2] E. Seedhouse, “Spaceports around the world,” in *Spaceports Around the World, A Global Growth Industry*, SpringerBriefs in Space Development, E. Seedhouse, Ed. Cham: Springer International Publishing, 2017, pp. 101–113.

[3] African Union, “African Space Strategy: Towards Social, Political and Economic Integration,” *African Union*, 2017. [Online]. Available: www.au.int. [Accessed: 6-Jun-2021].

[4] D. Nolek and G. Finger, "Attracting 'New Space' to your spaceport," in *AIAA SPACE 2009 Conference and Exposition*, 2009 [Online]. Available: Aerospace Research Central, https://arc.aiaa.org. [Accessed: 10-Jun-2021].

[5] S. R. Diana, F. Farida, and I. Musdafia, "Selection of spaceport site in Indonesia: Good economic efficiency and contribution to local economic development," *Researchers World: Journal of Arts, Science and Commerce*, vol. IX, p. 65, October 2018.

[6] P. Selvidge, *From airport to spaceport: Designing for an aerospace revolution*. MA [Dissertation]. Tampa, University of South Florida, 2010. [Online]. Available: http://scholarcommons.usf.edu.

[7] M. Dachyar and H. Purnomo, "Spaceport site selection with analytical hierarchy process decision making," *Indian Journal of Science and Technology*, vol. 11, pp. 1–8, March 2018.

[8] B. S. Gulliver and G. W. Finger, "Spaceport infrastructure cost trends," in *AIAA SPACE 2014 Conference and Exposition*, 2014 [Online]. Available: Aerospace Research Central https://arc.aiaa.org. [Accessed: 10-Jun-2021].

[9] Civil Aviation Authority, "CAP1189: UK Government review of commercial spaceplane certification and operations," *Civil Aviation Authority*, 2014. [Online]. Available: http://www.caa.co.uk/. [Accessed: 9-Jun-2021].

[10] P. Freeborn, M. Kinnersley, and A. Zorina, "The ROCKOT launch vehicle—the competitive launch solution for small Earth observation satellites into low Earth orbits," *Acta Astronautica*, vol. 56, pp. 315–325, 2005.

[11] T. G. Roberts, "Spaceports of the World," *Aerospace Security*, Jan.2021. [Online]. Available: https://aerospace.csis.org/data/spaceports-of-the-world/. [Accessed: Jan. 10, 2021].

[12] G. Bernardi and A. Vecchiato, "Astronautics," in *Understanding Gaia*, Popular Astronomy, G. Bernardi, and A. Vecchiato Eds. Cham, Springer Praxis Books, 2019, pp. 105–115.

[13] M. Tugnoli, M. Sarret, and M. Aliberti, "Overview on micro launchers," in *European Access to Space: Business and Policy Perspectives on Micro Launchers*, SpringerBriefs from the European Space Policy Institute, M. Tugnoli, M. Sarret, and M. Aliberti, Eds. Cham, Springer International Publishing, 2019, pp. 5–28.

[14] A. M. Anderson, M. Fehlinger, K. Harris, R. Rogers, and D. Valletta, "Spaceport design on the moon: From first launch to the future," in *ASCEND 2020*, 2020 [Online]. Available: Aerospace Research Central https://arc.aiaa.org. [Accessed: 5-Jun-2021].

[15] S. Cass and R. Schooff, "Paper session II-C - alternative launch site selection," in *Proceedings of 36th Space Congress: Countdown to the Millennium*, 1999, pp. 1–9.

[16] D. Webber, "The new commercial spaceports," in *AIAA SPACE 2004 Conference and Exhibit*, 2004 [Online]. Available: Aerospace Research Central https://arc.aiaa.org. [Accessed: 15-Jun-2021].

[17] I. Perwitasari, "Indonesia spaceport selection based on multicriteria analysis: A study on relative importance and priority regarding spaceport selection location attributes utilizing AHP," in *Proceedings of the 3rd International Conference on Indonesian Social & Political Enquiries*, *ICISPE 2018*, 2018, pp. 41–45.

[18] K. T. Atanassov, "Intuitionistic fuzzy sets," *Fuzzy Sets Systems*, vol. 20, pp. 87–96, August 1986.

[19] R. R. Yager, "Pythagorean membership grades in multicriteria decision making," *IEEE Transactions on Fuzzy Systems*, vol. 22, pp. 958–965, 2014.

[20] X. Zhang and Z. Xu, "Extension of TOPSIS to multiple criteria decision making with pythagorean fuzzy sets," *International Journal of Intelligent Systems*, vol. 29, pp. 1061–1078, 2014.

[21] S. Zeng, J. Chen, and X. Li, "A hybrid method for pythagorean fuzzy multiple-criteria decision making," *International Journal of Information Technology & Decision Making*, vol. 15, pp. 403–422, 2016.

[22] X. Peng and Y. Yang, "Fundamental properties of interval-valued pythagorean fuzzy aggregation operators," *International Journal of Intelligent Systems*, vol. 31, pp. 444–487, October 2015.

[23] T. L. Saaty, "Analytic Hierarchy Process," *Encyclopedia of Biostatistics*, July 2005.

[24] E. Ilbahar, A. Karaşan, S. Cebi, and C. Kahraman, "A novel approach to risk assessment for occupational health and safety using pythagorean fuzzy AHP & fuzzy inference system," *Safety Science*, vol. 103, pp. 124–136, 2018.

[25] C.-L. Hwang and K. Yoon, "Methods for multiple attribute decision making," in *Lecture Notes in Economics and Mathematical Systems*, C.-L. Hwang and K. Yoon, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 1981, pp. 58–191.

[26] S. Cevik Onar, B. Oztaysi, and C. Kahraman, "Multicriteria evaluation of cloud service providers using pythagorean fuzzy TOPSIS," *Journal of Multiple-Valued Logic and Soft Computing*, vol. 30, pp. 263–283, 2018.

[27] L. Pérez-Domínguez, L.A. Rodríguez-Picón, A. Alvarado-Iniesta, D. Luviano Cruz, Z. Xu, "MOORA under Pythagorean Fuzzy Set for Multiple Criteria Decision Making," *Complexity*, pp. 1–10, 2018.

[28] A. Hadi-Vencheh and M. Mirjaberi, "Fuzzy inferior ratio method for multiple attribute decision making problems," *Information Sciences*, vol. 277, pp. 263–272, 2014.

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