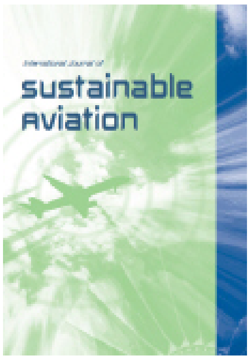

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Analysis of vertical flight efficiency in European countries with extended intuitionistic fuzzy TOPSIS method

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Abstract: Flight efficiency is an important policy design criterion in air traffic management systems. The efficiency of flight operations becomes an important factor in identifying bottlenecks and restrictions imposed by air traffic management on the flight trajectories preferred by the airspace user. In particular, measures for fuel-efficient operations are of great interest. In this study, the vertical efficiency criteria and performances of flights in European countries are examined with the extended intuitionistic fuzzy TOPSIS method. In light of the data presented by EUROCONTROL, the weights of the vertical efficiency evaluation criteria according to their importance levels were calculated. Vertical efficiency performance values of each country were measured. In addition, a comparison of the pre-and post-pandemic periods was made. According to the results of the study, the total CO_2 delta resulting from the flight level in descending and climbing was determined as the most important criterion in the vertical efficiency evaluation. In the country ranking, Luxembourg has the highest value in vertical efficiency performance in air traffic management. It is expected that the results of the research will guide decision-makers in air traffic management and contribute to the gap in the literature.

Keywords: vertical efficiency; intuitionistic fuzzy logic; aviation; multi-criteria decision-making; MCDM; EIFTOPSIS; continuous climb operation; CCO; continuous descent operation; CDO.

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1 Introduction

The efficiency of flight operations is becoming a critical factor for air traffic management and airspace users. International aviation organisations are evaluating orbital flight efficiency measurements to identify improvement opportunities for air traffic management systems. In general, flight efficiency aims to provide the most efficient trajectory to airspace users on the day of operation. The European Performance Program calculates a trajectory measure of horizontal flight inefficiency. Horizontal inefficiency, an indicator of a direct flight, shows the degree to which the flight distances between two cities increase or decrease. Although the evaluation of direct flight is the primary indicator for flight efficiency, both the FAA and international organisations such as EUROCONTROL have developed vertical flight efficiency analysis procedures to turn all orbital inefficiency into a fuel advantage. Flight efficiency measures are produced in the USA and Europe to identify strategic opportunities to improve flight trajectories (Peeters et al., 2016).

In this article, the vertical flight efficiency procedure developed and published by EUROCONTROL using the extended intuitionistic fuzzy TOPSIS (EIFTOPSIS) method is evaluated. In the two-stage implementation, firstly, the importance levels of vertical flight efficiency criteria were determined. In the second stage, the vertical flight efficiency scores of the European Countries were calculated and the performance ranking was made for the air traffic management communities. The originality value of this study can be explained as follows. The research is based on the vertical flight efficiency procedure developed by EUROCONTROL (2022). Although there are certain evaluation criteria for vertical flight efficiency, there is no study on the importance levels of these criteria. In the article, the importance weights of vertical flight efficiency criteria are calculated according to a relatively new method, EIFTOPSIS. For the first time, the air traffic management systems of European countries were reported according to their vertical flight efficiency values. Four years, including before and after the pandemic, were examined. The study includes results confirming the applicability of the EIFTOPSIS algorithm in vertical flight efficiency analysis at European airports in the periods covering the years 2019–2022. The sections of the article are planned as follows. First, after reviewing the relevant literature, the vertical flight efficiency procedure and criteria are presented. In the next step, the methods and algorithms used in the research are explained. Then, analysis and findings are given. In the last stage, research results and recommendations were mentioned.

2 State-of-art in vertical flight efficiency

The performance of air traffic management and especially the evaluation of flight efficiency has been the subject of interest in recent years. When the air flight efficiency literature is examined, it will be useful to mention some studies that will contribute to the research.

Wubben and Busink (2000) examined fuel savings in air flight efficiency compared to conventional procedures. In the research, it has been reported that there is a 25%–40% reduction in fuel consumption with the continuous descent approach.

Shresta et al. (2009) confirmed that at the airports under study, continuous descent operation (CDO) can significantly reduce fuel consumption and noise impact during the arrival phase by keeping the incoming aircraft at cruising altitude longer and performing a continuous descent.

Robinson and Kamgarpour (2010) explored the potential benefits of sustained landing at 25 major airports in the National Airspace System. They focused on modelling landing trajectories in terms of time and distance. The results show that time-constrained orbits show 70%–85% less potential savings than distance-constrained orbits

Cao et al. (2011) explored the principles of continuous descent to strategically eliminate conflicts in the 4D concept and different forms of planning using a programming algorithm.

Knorr et al. (2011) investigated the contribution of reducing the speed while cruising to minimise the inefficiencies caused by waiting during the landing of the aircraft. In the study, both vertical and horizontal inefficiency components were evaluated within 100NM of the destination airport to calculate the potential fuel savings per flight based on time inefficiency. In the article, level flight (vertical component) and excess distance (horizontal component) were identified as the two main indicators of inefficiency. The results of the research show that the inefficiencies identified at busy airports such as New York airports are related to the need to sort aircraft (Knorr et al., 2011).

An algorithm has been developed by Chatterji (2011) that predicts flight inefficiency mostly in terms of extra fuel consumption during the road flight phase.

Ryerson et al. (2014) examined actual flight-level fuel consumption data reported by a US-based airline to examine possible fuel savings from air traffic management improvements. It ranked the terminal areas by determining terminal inefficiency according to a metric based on the variation in fuel consumed between flights.

Reynolds (2014) described the importance of measuring ATM system performance to understand its current and potential future role in reducing the environmental impacts of air transport. Discussing flight inefficiency measurements within the framework of a range of flight dimensions, Reynolds stated that fuel-based metrics are much more meaningful in terms of environmental impacts, but their calculations are complex. The research results provide information on which elements of the ATM system should be prioritised in future policy determinations to reduce environmental impacts.

Fricke et al. (2015) evaluated German Airports in terms of fuel efficiency using radar tracking data. He proposed analytical models based on local traffic and meteorological conditions to improve CDOs.

EUROCONTROL has developed a comprehensive framework for characterising horizontal and vertical flight efficiency during climb and descent by the performance review unit (PRU). The horizontal dimension is based on the concepts of sequencing of arrival, which is an area of 40 NM from the airport, and unobstructed time in the measurement area and additional time. It is based on analysis of continuous descent/climb segments with indicators such as vertical size, distance, and time-of-flight level, median sustained descent/climb altitude, and percentage of flights performing sustained descent/climb. This methodology is used to evaluate and compare the performances of arrival management at major airports in Europe (EUROCONTROL, 2017).

Howell and Dean (2017) examined vertical efficiency changes at 30 US-based airports for 2010 and 2015 through optimised profile descent and terminal area measurement. Modelling was used in the study to estimate potential savings in time and fuel. A 30% fuel saving was observed in the research results.

A performance indicator set has been proposed to measure fuel inefficiencies by Prats et al. (2019). In practice, vertical inefficiency in the descending phase has been found to result from the inability of flights to sustain sustained descent operation (CDO). CDO operations provide optimum continuous engine idle landings that reduce fuel consumption, gas emissions, and noise disturbance by ensuring an optimised flight profile is run according to the aircraft's operating capability (Lemetti et al., 2020).

Zanin (2020) evaluated the efficiency of flights landing at an airport using large-scale open datasets of aircraft trajectories. The researcher focused on understanding the efficiency of different airspaces and comparing them. The article shows how large datasets can be used to understand the actual behaviour of the system and the deviation from the planned state.

Pasutto et al. (2020) examined the factors affecting vertical efficiency in landing at Europe's top 30 airports. The article reveals that the vertical deviation increases with the horizontal deviation, and the vertical deviation is distributed for the same horizontal deviation. In the analysis results, it is noticed that there is a very important inequality between airports, and some indicators change five times or more. Vertical flight efficiency has received more attention in recent years, especially after the implementation of additional flow measures to manage the capacity crisis in 2018/19 (EUROCONTROL, 2020).

Developed the methodology for vertical flight efficiency analysis during climb and descent by the EUROCONTROL PRU. The EUROCONTROL Performance Review Commission examined air traffic punctuality and vertical flight inefficiency at 30 of Europe's top airports in 2018. EUROCONTROL PRU offers a cloud-based open access repository to re-evaluate the performance review results of stakeholders (Spinielli et al., 2018).

Vertical inefficiencies in the descent phase are due to the inability of flights to follow CDOs. CDOs ensure the execution of an optimised flight profile based on the aircraft's operating capability, resulting in optimum continuous landings with the engine idling. The descent is considered vertically inefficient when aircraft ascend at moderate altitudes before landing (Lemetti et al., 2023). One of the most important causes of fuel wastage in flights is ineffective vertical flight profiles. The colder and less dense air at high altitudes increases aircraft performance. At high altitudes, the aircraft can fly faster and burn less fuel. Therefore, the main assumption for the analysis of vertical flight efficiency during landing, all other factors being equal, is that level flight is considered inefficient (Lemetti et al., 2019). In this framework, the ideal flight is a continuous ascent or descent with flights rising to the ideal fuel-burning altitude without flight level limitation due to air traffic management restrictions (Peeters et al., 2016).

3 Method

The fuzzy set (FS) theory proposed by Zadeh (1965) has been widely used in various fields of economy, management, and industry as an effective tool to get rid of ambiguity and uncertainty. The most distinctive feature of Zadeh's FS is that the membership degrees of the cluster elements are taken into account. Recently, some extensions of traditional FS theory have been developed and different applications have been made. As one of the well-known extensions of the traditional fuzzy set, the intuitionistic fuzzy set (IFS) proposed by Atanassov (1986) is characterised by the degree of membership, degree of non-membership, and degree of hesitation. Many researchers state that the IFS approach offers meaningful results in dealing with fuzziness and is very useful in applications (Shen et al., 2016).

Multi-criteria decision-making (MCDM) provides a systematic quantitative approach to decision-making problems involving multiple criteria and actions. MCDM can assist decision-makers in rationally evaluating all-important objective and subjective criteria for a problem (Hatami-Marbini and Tablo, 2011). TOPSIS, first introduced by Hwang and Yoon (1981), is one of the best-known classical MCDM approaches. The basic assumption of the TOPSIS approach is that the most preferred alternative is both the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution (Onat et al., 2016). In classical TOPSIS methods, precise numerical values are used to express the performance rating of the criteria. Recently, the combination of the TOPSIS method and IFSs has received widespread attention from many researchers (Shen et al., 2018). However, the proposed TOPSIS methods in the intuitionistic fuzzy environment have some disadvantages such as not being able to take an alternative order of preference and negative effects in the real decision-making process (Ye, 2010; Joshi and Kumar, 2014; Wang et al., 2016).

Decision makers cannot make decisions using some existing distance measures. The results calculated by the available distance measures do not meet the specifications of the distance measures. In some cases, it is not possible for the decision makers to reach a decision because the distance measure between the alternatives is equal in the existing methods. In summary, there are some problems with the use of existing distance measures in the decision-making process.

In this study, the intuitionistic fuzzy distance measure, which was proposed by Shen et al. (2018) and, which overcomes the drawbacks of the existing IFS distance measure, was used. The basic algorithm of the IFS approach is given below.

For any $x \in X$ where $A = \{(x, \mu A\ (x), \nu A\ (x))\ |x \in X\}$ for the IFS A in the set X;

$$\mu_A : X \to [0,1], x \in X \to = \mu_A(x) \in [0,1] \tag{1}$$

the degree of membership of $x \in X$ to A

$$v_A : X \to [0,1], x \in X \to = v_A(x) \in [0,1], \tag{2}$$

the degree of non-membership of $x \in X$ to A, and

$$\mu_A(x) + v_A(x) \leq 1 \tag{3}$$

is expressed.

The degree of hesitation or uncertainty of X in A is calculated by the function $\pi_A(x) = 1 - \mu_A(x) - \nu_A(x)$ (Atanassov, 1986). Especially if $\pi_A(x) = 0$, A is reduced to a fuzzy set.

In MCDM problems, decision-makers need to weigh more than one criterion according to the level of importance and choose the most appropriate one among various alternatives. Among the MCDM methods, the TOPSIS method attracts a lot of attention. The Extended Intuitionistic Fuzzy TOPSIS (EIFTOPSIS) approach based on the new distance measure is preferred to be used in this article because of its effective results and advantages. The application procedure and mathematical notations of the EIFTOPSIS method, which is integrated with the extended intuitionistic fuzzy approach, are presented below (Shen et al., 2018).

Step 1 A decision matrix is created that includes row-based competitive alternatives (*i*) and column-based criteria (*j*).

$$D = \left(a_{ij}\right)_{m\times n} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_i \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_j \end{array} \\ \begin{pmatrix} a_{11} & a_{12} & \cdots & C_j \\ a_{21} & a_{22} & \cdots & a_{1j} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} \end{pmatrix} \end{array} \tag{4}$$

Step 2 Each value in the decision matrix is normalised with the help of equation (5) (Jahanshahloo et al., 2006). The application example of equality is as follows.

$$\mu_{ij} = x_{ij} \Big/ \sqrt{\sum_{j=1}^{m} x_{ij}^2} \quad i = 1\ldots, m. \quad j = 1, \ldots, n \tag{5}$$

$$0.153 = 1000 \big/ \sqrt{1000^2 + 810^2 + 366^2 + \ldots + 447^2}$$

Step 3 The exact data in the normalised decision matrix are transformed into intuitionistic fuzzy values by using equations (6) to (8) respectively (Atanassov, 1986; Singh et al., 2019). The application example of equality is as follows.

$$v_i' = 1 - \mu_i \tag{6}$$

$$0.847 = 1 - 0.153$$

$$\pi_i = \frac{v_i'}{\sum_{i=1}^{n} v_i'} \tag{7}$$

$$0.024 = \frac{0.847}{0.847 + 0.877 + 0.944 + \cdots + 0.932}$$

$$v_i = 1 - \mu_i - \pi_i \tag{8}$$

Step 4 IFSs-based positive ideal solution values for each criterion are calculated using $\tilde{a}^+ = \tilde{a}_1^+, \tilde{a}_2^+, \ldots, \tilde{a}_n^+$, and negative ideal solution values $\tilde{a}^- = \tilde{a}_1^-, \tilde{a}_2^-, \ldots, \tilde{a}_n^-$ using equations (9) and (10), respectively. C^+ refers to the benefit cluster criteria and C^- refers to the cost cluster criteria in the equations.

$$\tilde{a}_j^+ = \begin{cases} \left(\max_{1\le i\le m}\left\{\mu_{ij}\right\}, \min_{1\le i\le m}\left\{v_{ij}\right\}\right) = \left(\mu_j^+, v_j^+\right), & if\ C_j \in C^+ \\ \left(\min_{1\le i\le m}\left\{\mu_{ij}\right\}, \max_{1\le i\le m}\left\{v_{ij}\right\}\right) = \left(\mu_j^+, v_j^+\right), & if\ C_j \in C^- \end{cases} \tag{9}$$

$$\tilde{a}_j^- = \begin{cases} \left(\min_{1\le i\le m}\left\{\mu_{ij}\right\}, \max_{1\le i\le m}\left\{v_{ij}\right\}\right) = \left(\mu_j^-, v_j^-\right), & if\ C_j \in C^+ \\ \left(\max_{1\le i\le m}\left\{\mu_{ij}\right\}, \min_{1\le i\le m}\left\{v_{ij}\right\}\right) = \left(\mu_j^-, v_j^-\right), & if\ C_j \in C^- \end{cases} \tag{10}$$

Step 5 With the new distance measure shown in equations (11) to (12), the intuitionistic fuzzy distances between $\tilde{a}_{ij}, \tilde{a}_j$ and $\tilde{a}_{ij}, \tilde{a}_j^+$ are calculated separately. Then, intuitionistic fuzzy distance matrices (12) and (13) are generated.

$$\tilde{\mu}_{ij} = \mu_{ij}\left(1 + \frac{2}{3}\pi_{ij}\left(1 + \pi_{ij}\right)\right) \tag{11}$$

$$0.155 = 0.153\left(1 + \frac{2}{3}0.024(1 + 0.024)\right)$$

$$\tilde{v}_{ij} = v_{ij}\left(1 + \frac{2}{3}\pi_{ij}\left(1 + \pi_{ij}\right)\right) \tag{12}$$

$$0.835 = 0.821\left(1 + \frac{2}{3}0.24(1 + 0.24)\right)$$

$$D^+ = \left(d\left(\tilde{a}_{ij}, \tilde{a}_j^+\right)\right)_{m \times n} = \begin{array}{c c} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_j \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{pmatrix} d\left(\tilde{a}_{11}, \tilde{a}_1^+\right) & d\left(\tilde{a}_{12}, \tilde{a}_2^+\right) & \cdots & d\left(\tilde{a}_{1n}, \tilde{a}_n^+\right) \\ d\left(\tilde{a}_{21}, \tilde{a}_1^+\right) & d\left(\tilde{a}_{22}, \tilde{a}_2^+\right) & \cdots & d\left(\tilde{a}_{2n}, \tilde{a}_n^+\right) \\ \vdots & \vdots & \ddots & \vdots \\ d\left(\tilde{a}_{m1}, \tilde{a}_1^+\right) & d\left(\tilde{a}_{m2}, \tilde{a}_2^+\right) & \cdots & d\left(\tilde{a}_{mn}, \tilde{a}_n^+\right) \end{pmatrix} \end{array} \tag{13}$$

$$D^- = \left(d\left(\tilde{a}_{ij}, \tilde{a}_j^-\right)\right)_{m \times n} = \begin{array}{c c} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_j \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{pmatrix} d\left(\tilde{a}_{11}, \tilde{a}_1^-\right) & d\left(\tilde{a}_{12}, \tilde{a}_2^-\right) & \cdots & d\left(\tilde{a}_{1n}, \tilde{a}_n^-\right) \\ d\left(\tilde{a}_{21}, \tilde{a}_1^-\right) & d\left(\tilde{a}_{22}, \tilde{a}_2^-\right) & \cdots & d\left(\tilde{a}_{2n}, \tilde{a}_n^-\right) \\ \vdots & \vdots & \ddots & \vdots \\ d\left(\tilde{a}_{m1}, \tilde{a}_1^-\right) & d\left(\tilde{a}_{m2}, \tilde{a}_2^-\right) & \cdots & d\left(\tilde{a}_{mn}, \tilde{a}_n^-\right) \end{pmatrix} \end{array} \tag{14}$$

Step 6 The composite intuitionistic fuzzy distance matrix $D^* = D^- - D^+$ (15) is generated. In the best performance data, $d(\tilde{a}_{ij}, \tilde{a}_j^-)$ values should be large and $d(\tilde{a}_{ij}, \tilde{a}_j^+)$ values should be small. In other words, the data with the best performance should be far from the cost criteria and close to the benefit criteria. The larger the Z_{ij}^* value, the better the $\tilde{a}_{ij}$ performance data indicates

$$\begin{aligned} D^* = \left(Z_{ij}^*\right)_{m \times n} &= \begin{array}{c c} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{pmatrix} d\left(\tilde{a}_{11}, \tilde{a}_1^-\right) - d\left(\tilde{a}_{11}, \tilde{a}_1^+\right) & d\left(\tilde{a}_{12}, \tilde{a}_2^-\right) - d\left(\tilde{a}_{12}, \tilde{a}_2^+\right) & \cdots & d\left(\tilde{a}_{1n}, \tilde{a}_n^-\right) - d\left(\tilde{a}_{1n}, \tilde{a}_n^+\right) \\ d\left(\tilde{a}_{21}, \tilde{a}_1^-\right) - d\left(\tilde{a}_{21}, \tilde{a}_1^+\right) & d\left(\tilde{a}_{22}, \tilde{a}_2^-\right) - d\left(\tilde{a}_{22}, \tilde{a}_2^+\right) & \cdots & d\left(\tilde{a}_{2n}, \tilde{a}_n^-\right) - d\left(\tilde{a}_{2n}, \tilde{a}_n^+\right) \\ \vdots & \vdots & \ddots & \vdots \\ d\left(\tilde{a}_{m1}, \tilde{a}_1^-\right) - d\left(\tilde{a}_{m1}, \tilde{a}_1^+\right) & d\left(\tilde{a}_{m2}, \tilde{a}_2^-\right) - d\left(\tilde{a}_{m2}, \tilde{a}_2^+\right) & \cdots & d\left(\tilde{a}_{mn}, \tilde{a}_n^-\right) - d\left(\tilde{a}_{mn}, \tilde{a}_n^+\right) \end{pmatrix} \end{array} \\ &= \begin{array}{c c} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{pmatrix} Z_{11}^* & Z_{12}^* & \cdots & Z_{1n}^* \\ Z_{21}^* & Z_{22}^* & \cdots & Z_{2n}^* \\ \vdots & \vdots & \ddots & \vdots \\ Z_{m1}^* & Z_{m2}^* & \cdots & Z_{mn}^* \end{pmatrix} \end{array} \end{aligned} \tag{15}$$

Step 7 $w^*_{ij}\,(j = 1, 2, \ldots, n)$ importance weights are calculated for each criterion. The basis of weights reflects relative importance. Methods for determining criteria weights fall into three categories, the first includes subjective methods in which the importance of criteria is assigned by the decision maker; Second, objective methods in which weights are obtained based on the data of the recognised problem. The third method is to combine the subjective method with the objective method. In this paper, the maximum deviation method is used to determine the weight for each criterion, which is one of the objective methods. The maximising deviation method was proposed by Yingming (1997) to solve MCDM problems with numerical information. The essence of this approach is that if the performance values of each alternative have minor differences under a criterion, that criterion plays a smaller role in choosing the best alternative. If there is a large difference between different alternatives in a criterion, such a criterion plays an important role in choosing the best alternative.

The mathematical notation of the maximum deviation method is shown in equation (16). In this method, decision makers derive the weights of the criteria from the variability of the data. w^*_j shows the optimal weight for each criterion.

$$w^*_j = \frac{\sum_{i=1}^{m} \sum_{k=1}^{m} \left| Z_{ij} - Z_{kj} \right|}{\sum_{j=1}^{n} \sum_{i=1}^{m} \sum_{k=1}^{m} \left| Z_{ij} - Z_{kj} \right|} \tag{16}$$

Step 8 The weighted intuitionistic fuzzy distance measures of each alternative are calculated with the help of equation (17). At the last stage in the application procedure of the method, the alternatives are ranked according to the $\tilde{D}_i$ score. The higher the $\tilde{D}_i$ value, the better the alternative's performance.

$$\tilde{D}_i = \sum_{j=1}^{n} w^*_j Z^*_{ij}, \quad i = 1, 2, \ldots, m. \tag{17}$$

4 Application

Due to the complexity of decision-making problems, the preferences of decision-makers, and the different characteristics of the criteria, methods of supporting decision-makers are applied extensively. Ensuring efficiency in flight operations, which is a complex process, is one of the priority issues of International Aviation Management Organizations. In this study, vertical flight efficiency levels in air traffic management of 40 European countries were examined. Within the scope of the analysis, key indicators recommended by the EUROCONTROL PRU were used. The criteria used in the vertical flight efficiency performance ranking are presented in Table 1. The first 10 basic indicators (C1–C10) in the table are related to the descent process in flight and the other indicators (C11–C20) are related to the climbing process in flight.

Table 1 Evaluation criteria

Code	*Column description*	*Data source*
C1	Number of arriving flights	PRU
C2	Total distance flown level during descent in nautical miles	PRU
C3	Total distance flown level during descent below FL075 in nautical miles	PRU
C4	Total time flown level during descent in seconds	PRU
C5	Total time flown level during descent below FL075 in seconds	PRU
C6	Median CDO altitude in feet	PRU
C7	Number of flights that are considered CDO during the whole descent (and don't have any considered level flight)	PRU
C8	Number of flights that are considered CDO below FL075 (and don't have any considered level flight below FL075)	PRU
C9	Total delta of CO_2 (kg) resulting from the time flown level in descent	PRU
C10	Total delta of CO_2 (kg) resulting from the time flown level below FL075 in descent	PRU
C11	Number of departing flights	PRU
C12	Total distance flown level during climb in nautical miles	PRU
C13	Total distance flown level during climb below FL105 in nautical miles	PRU
C14	Total time flown level during climb in seconds	PRU
C15	Total time flown level during climb below FL105 in seconds	PRU
C16	Median CCO altitude in feet	PRU
C17	Number of flights that are considered CCO during the whole climb (and don't have any considered level flight)	PRU
C18	Number of flights that are considered CCO below FL105 (and don't have any considered level flight below FL105)	PRU
C19	Total delta of CO_2 (kg) resulting from the time flown level in climb	PRU
C20	Total delta of CO_2 (kg) resulting from the time flown level below FL075 in climb	PRU

Forty four countries in Europe have air management systems. In this study, the air traffic management systems of 40 European countries, shown in Table 2, are included as the decision-making unit (DMU). Due to the deficiencies in the research data, 4 European countries were excluded from the analysis.

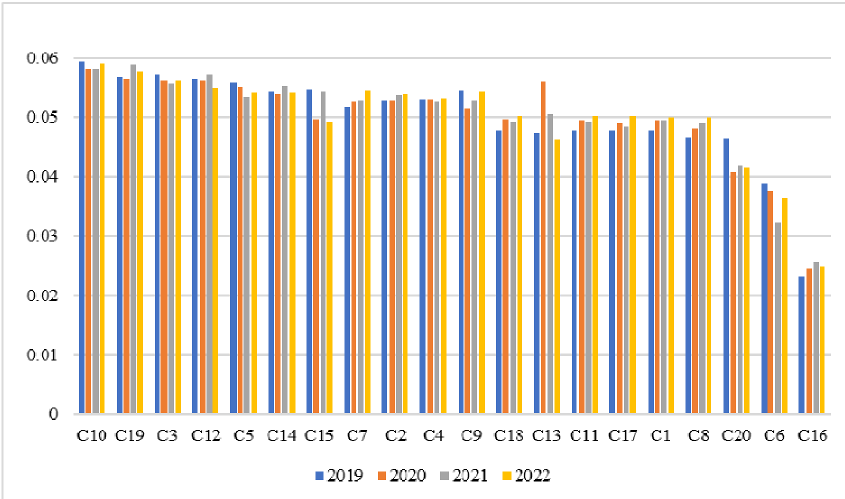
Vertical efficiency data for 2019–2022 presented by EUROCONTROL PRU were analysed with the EIFTOPSIS method. In the EIFTOPSIS application, first of all, criterion weight values were calculated. In Figure 1, the importance weight levels of the criteria by years are presented. The total CO_2 delta (C10) at 7,500 feet flight level during the descent phase and the total CO_2 delta (C19) during the climb phase are the criteria with the highest importance. The CO_2 delta (C20) occurring at the 7,500 feet level climb has comparatively lower importance weights to the other criteria.

It is known that the amount of level flight that occurs in the vertical flight profile at levels where the main environmental impact is present is much higher in the descending phase than in the climb phase (EUROCONTROL, 2021). In this case, it is thought that the CO_2 emission at the level of descent has more environmental impact.

Table 2 Evaluated decision units

Code	*Country*	*Code*	*Country*	*Code*	*Country*	*Code*	*Country*	*Code*	*Country*
DMU1	Belgium	DMU9	Luxembourg	DMU17	Albania	DMU25	Slovenia	DMU33	Switzerland
DMU2	Germany	DMU10	Norway	DMU18	Bulgaria	DMU26	Czech Republic	DMU34	Moldova
DMU3	Estonia	DMU11	Poland	DMU19	Cyprus	DMU27	Israel	DMU35	Macedonia
DMU4	Finland	DMU12	Sweden	DMU20	Croatia	DMU28	Malta	DMU36	Serbia
DMU5	UK	DMU13	Latvia	DMU21	France	DMU29	Austria	DMU37	Slovakia
DMU6	Netherlands	DMU14	Lithuania	DMU22	Greece	DMU30	Portugal	DMU38	Armenia
DMU7	Ireland	DMU15	Spain	DMU23	Hungary	DMU31	Bosnia and Herzegovina	DMU39	Georgia
DMU8	Denmark	DMU16	Morocco	DMU24	Italy	DMU32	Romania	DMU40	Ukraine

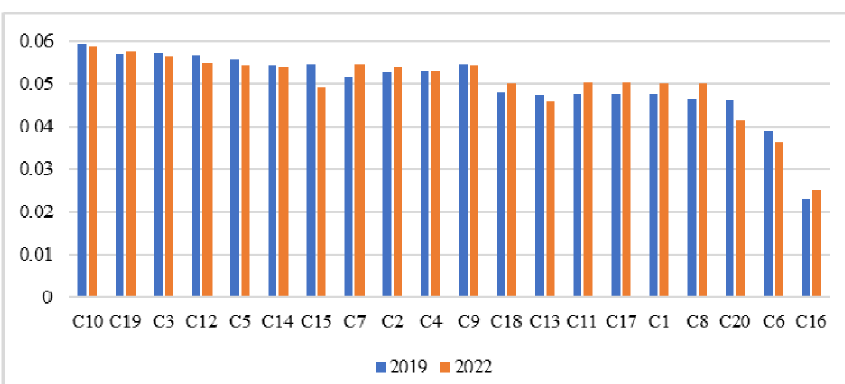
Figure 1 Criterion significance weights (see online version for colours)



Carbon dioxide gas, which is one of the most important environmental effects of aviation on the climate, is a global problem due to its long residence time in the atmosphere. It is estimated that aviation is responsible for approximately 2.5% of total CO_2 emissions globally (Ritchie, 2020).

The lowest importance weight is noticed in the median altitude criterion. The median altitude in the process of descent (CDO) has a higher weight of importance than the median altitude in climb [continuous climb operation (CCO)]. The median altitude considers the altitude of the lowest level segment during ascent or descent for a given flight. In both cases, a higher mid-altitude is desirable, as level dips at lower altitudes lead to more fuel burn and noise pollution (Peeters et al., 2018).

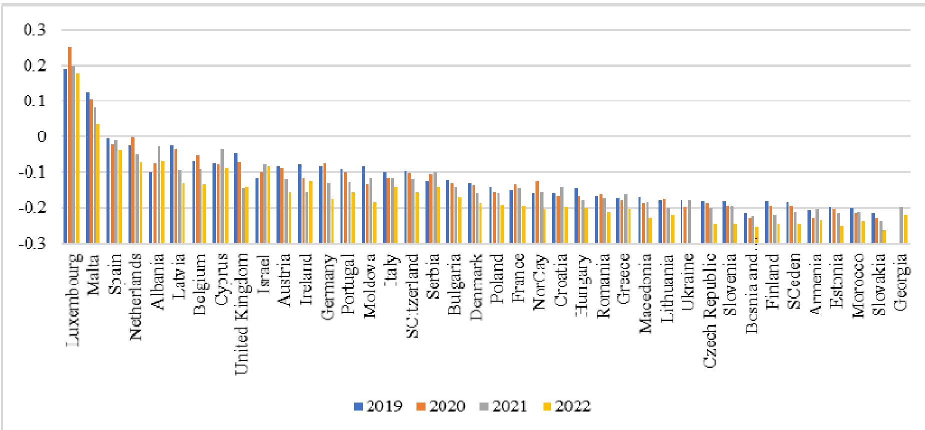
Figure 2 Criterion significance weights (pre-pandemic – post pandemic) (see online version for colours)



As seen in Figure 2, no consistent change was noticed in the criteria weights in the pre- and post-pandemic periods. Before and after the pandemic, the importance weights of some criteria increased, while others decrease.

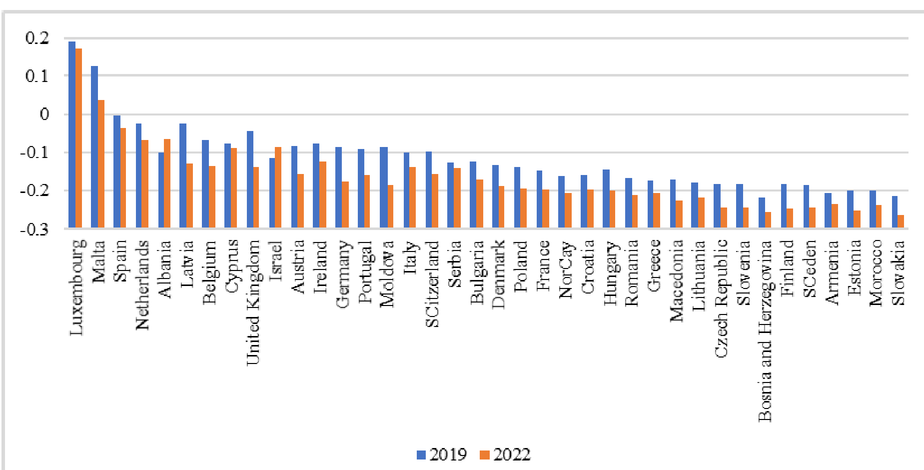
When Figure 3 is examined, it is understood that the highest performance in vertical flight efficiency is displayed in Luxembourg air traffic management. It is seen that Slovakia has the lowest vertical flight efficiency among European countries in vertical flight efficiency.

Figure 3 Vertical flight efficiency ranking (see online version for colours)



According to Figure 4, vertical flight efficiency values of Albania and Israel are increasing compared to the pre-pandemic period. Vertical flight efficiency scores in all other countries are decreasing compared to pre-pandemic. In the pre- and post-pandemic period, the least change in vertical flight efficiency occurred in Luxembourg and Cyprus, while the most changes were recorded in Moldova.

Figure 4 Vertical flight efficiency ranking (pre-pandemic – post pandemic) (see online version for colours)



5 Conclusions

Ensuring efficiency in flight operations is one of the priority issues of International Aviation Management Organizations. In this study, the vertical flight efficiency of the air traffic management of European Countries was examined with the EIFTOPSIS method over 4 years. In the analysis, the general situation assessment of air traffic management in the COVID-19 process was also reported. The results of this study provide supporting information for countries to manage vertical flight inefficiency in air traffic management and to carry out optimisation activities in related fields.

Continuous ups and downs in the efficiency of flight operations are defined as one of the improvement steps in aviation management. Airspace users are interested in improvement studies for horizontal and vertical efficiency variables. By improving vertical flight efficiency, positive effects are provided on flight operations, fuel savings, carbon emission reduction, and the noise contour in and around airports.

As the results of this study support, air pollutant emissions have a non-negligible effect on flight efficiency. The emission values that occur during the flight are important both in terms of cost and efficiency. Reducing emissions is one of the most important points to focus on when trying to optimise air transport. Emission gas released to the environment in aviation operations is directly related to fuel consumption. Lower fuel consumption will result in lower emissions. In order to achieve the CO_2 emission targets set in global aviation policies, it is supported to increase flight efficiency based on fuel consumption. Reducing the noise in flight operations may cause the passengers who are sensitive to noise to prefer the airline for their travels.

According to the results obtained in the second phase of the research, Luxembourg is the country with the best performance in vertical flight efficiency. Luxembourg airport is home to Europe's fifth largest air transport hub, which has grown steadily in recent years. About 10% of the world's major cargo planes operate in the Luxembourg air management system. As noted in Baxter's (2022) study, Cargolux Airlines International attended the inaugural meeting to establish CDO at Luxembourg Airport in 2018. The case study showed that jet fuel consumption could be optimised thanks to Cargolux Airlines International's advanced air traffic control management measures. As a result of the studies, systems that provide significant savings in CDO and aircraft flight times were implemented at Luxembourg Airport. In addition, Luxembourg is among the best European countries in the evaluation of indices focusing on the level of digital transformation in aviation. Luxembourg's best performance in vertical flight efficiency reflects the positive impact of the measures and practices taken. Luxembourg aviation management system applications can be an example for other countries to increase their flight efficiency. It is important to use the right criteria to realise the applications and goals based on scientific studies.

All stakeholders in the aviation industry have been affected by the pandemic. The COVID-19 pandemic has caused an unprecedented reduction in air traffic. After the epidemic, traffic volumes in aviation started to be regained gradually (Lemetti et al., 2023). Although air traffic volumes decreased during the COVID-19 process, there was no steady change in vertical flight efficiency in the results of the study. Although the COVID-19 pandemic has halved CO_2 emissions from aviation in 2020 and 2021, it is clear that the environmental challenge for aviation will continue throughout the recovery phase and beyond. This is because the relative share of aviation in total CO_2 emissions continues to increase, as carbon emissions are expected to decline more rapidly in other sectors. It is thought that improving efficiency along with reducing fuel use and CO_2 emissions will maintain its importance as a focus for the recovery of the aviation industry after the COVID-19 crisis.

Due to the specificity of the research topic, there is no similar or close study to be compared in the literature. Due to this limitation, no comparison could be made in the research results.

Comparison of the analyses by adding variables such as cost, load weight, etc. in the flight efficiency evaluation can be preferred as a good topic for future research. The results can be compared by using different methods in future studies aimed at development and improvement in the aviation industry. More comprehensive studies involving all stakeholders can be included.

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List of abbreviations

Abbreviation	*Definition*
ATC	Air traffic control
ATM	Air traffic management
CDO	Continuous descent operation
CCO	Continuous climb operation
DMU	Decision-making unit
EIFTOPSIS	Extended intuitionistic fuzzy TOPSIS
FAA	Federal aviation administration
FL	Flight level
IFS	Intuitionistic fuzzy set
MCDM	Multi-criteria decision-making
NM	Nautical mile
PRU	Performance review unit
TOPSIS	Technique for order preference by similarity to ideal solution