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AIM AND SCOPE

Journal of Aviation (JAV) established in 2017. It is a peer–reviewed international journal to be of interest and use to all those concerned with research in various fields of, or closely related to, Aviation science. Journal of Aviation (JAV) aims to provide a highly readable and valuable addition to the literature which will serve as an indispensable reference tool for years to come. The coverage of the journal includes all new theoretical and experimental findings in the fields of Aviation Science or any closely related fields. The journal also encourages the submission of critical review articles covering advances in recent research of such fields as well as technical notes.

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Impact of Operations on a Series per Reliability Perspective

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Abstract

The Mean Time Between Failure (MTBF) figures are the average of test durations between failure observations formed into a series. They can be seen to suit classical statistical distributions. An equally possible condition is that they are not stationary as a contradiction to the previous statement. In such worse conditions accepting availability of a concealed statistical property, this paper tries to identify the impact of *Bi-sample Differencing* and *Bi-sample mean* manipulations. In other words, operating on *reliability observations series* to reveal concealed statistical knowledge. Experimentation based on observation over a stationary series as a controlled experiment. As an outcome of experiments, the differencing seems to be alleviating the trend and seasonality to a degree. The bi-sample averaging is observed to be hiding variant conditions.

1. Introduction

Once we obtain an observation series, whether it is stationary or not is controlled. In cases that this quality is not found, differencing type of interventions by subtracting the same equation with a preceding indexed y_{t-1} from both sides of an Auto Regression (AR) equation with y_t is considered (Sun et al. 2021). The target is fixing the situation by altering nothing in a mathematically accurate sense. This is actually checking whether there is a hidden stationary character within the series like a trend by forming a derivative one (Worden et al. 2019).

Would such an approach be applicable to a reliability series is the question aimed at being answered. There are varieties of techniques for identifying a stationary trend; very few of the studies consider the effects of changes for predictions such as Mean time between failure (MTBF) identifications. Consideration is made in a controlled manner once the series is independent and identical distributed according to a known classical distribution (Yucesan et. al. 2021), with a known mean (μ) and variance (σ) from observations.

This is a time for failure observations allowing for the prediction of a meaningful probability of a worse outcome. When operational duration is 3σ below the MTBF, there is less than or about 0.0013 chance of something going wrong. Depending on application, chance may be sufficiently safe, or it can be bad if the frequency of demand is high enough (Yucesan et. al. 2022).

To speak with clarity of this sort, we need stationary signals. The trends and seasonalities might be ruining the signal, hiding the underlying stationary character (Basu et al. 2009). To get around hiding effects, one addresses the mentioned operations, which are actually very well-known called filtering. Nevertheless, they can have an impact on the useful information from the series. Mentioned operations can be of the sort of a high or a low pass characteristic manner, namely a differencing and an averaging filter in respective ordering. The paper aims at observing the impacts of the mentioned techniques including changes on stationarity as a tool of measurement based on various tests like Kwiatowski, Phillips, Schmidt and Shin (KPSS) or Augmented Dickey and Fuller Test (ADF). Considerations will include the mean and variance impacts along with the existence of heteroscedasticity. Finally, information change obtained from the series as a result of the filter operations based on frequency is sought.

The rest of the document is organised as: first section introduction is followed by section 2. Stationarity Test Outcomes and section 3 Frequency Impact. A discussion on the findings is provided in section 4. Discussions, including a literature consideration and the paper is finalised by section 5 Conclusions.

2. Stationarity Tests Outcomes

KPSS and ADF tests are frequently referred to in the literature. These tests performed by known software such as

MATLAB with built-in functions, which can present the case of the observations better. The Student-t test is performed to see if the distribution of a given series to mentioned manipulations is different than that of a normal distribution with zero (0) mean (μ) and unity variance ($\sigma^2 = 1$). The resultant series variances (σ^2) are compared by first forming a series with the overall constant of one multiplied by variance outcome. Later the deviations from the mean in each of this variance derived series in squared terms $(S_i-\mu)^2$ was compared to this constant series pairwise. Here the S_i term represent each sample of the series. The Engel Arch test for Heteroscedasticity was also employed.

Table 1. Results of the statistical tests.

Test	Stu-t-μ	Stu-t-σ^2	ADF	KPSS	W/O Trend	Engle Arch
Original	In-Diff.	In-Diff.	Stat.	Non.	Stat.	Homosc.
Difference	In-Diff.	In-Diff.	Stat.	Stat.	Stat.	Heterosc.
Bi-Sample Ave.	In-Diff.	In-Diff.	Non.	Non.	Non.	Heterosc.

The outline of the results from Tab. 1 indicates that the processes of differencing and averaging impact the series in stationarity perspective. ADF test identify the original and difference series as stationary, on the other hand, bi-sample average series to be non-stationary. The default application of the test KPSS considers trend as present in regression formula. It is also possible to turn this off and check for a normal regression stationarity. The test fails when there is a trend control but indicates stationarity as it is removed. Difference operation solves this problem and gives a stationary outcome in both cases. The series originally presents homoscedastic behavior indicative of a variance stationarity; however, both filter operations on them end up with heteroscedasticity as a result of the Engel test.

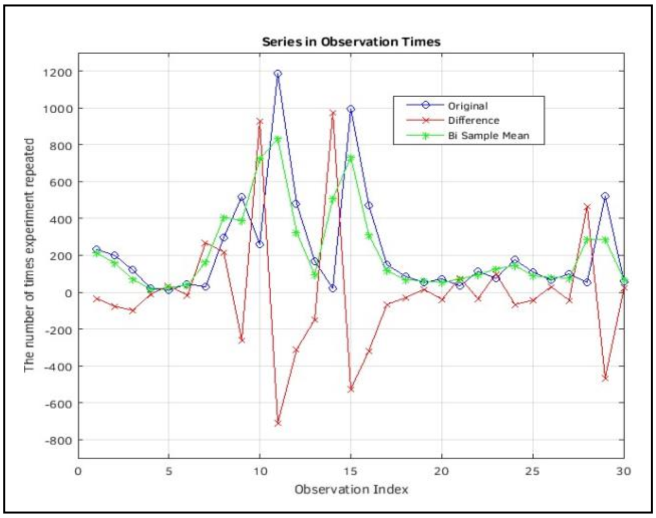

Figure 1. The observation series with 'o', the difference series is with 'x', and finally the bi-sample average series is marked with an asterisk '*'

The series subject to the study is composed from observations aiming to build up an MTBF figure. The same experiment of information query is repeated many times to see how many re-attempts can be made. As a failure occurs, the count of repetition is recorded, a reset is performed and the experiment is restarted. Based on these results, a data series from these observations is composed. The first 30 samples from all series are presented to give a basis of comparison in Fig. 1. The 'o' marked are from the original series, 'x' marked ones are from the series that is the outcome of the difference operations. '*' mark indicates the Bi-sample mean operations.

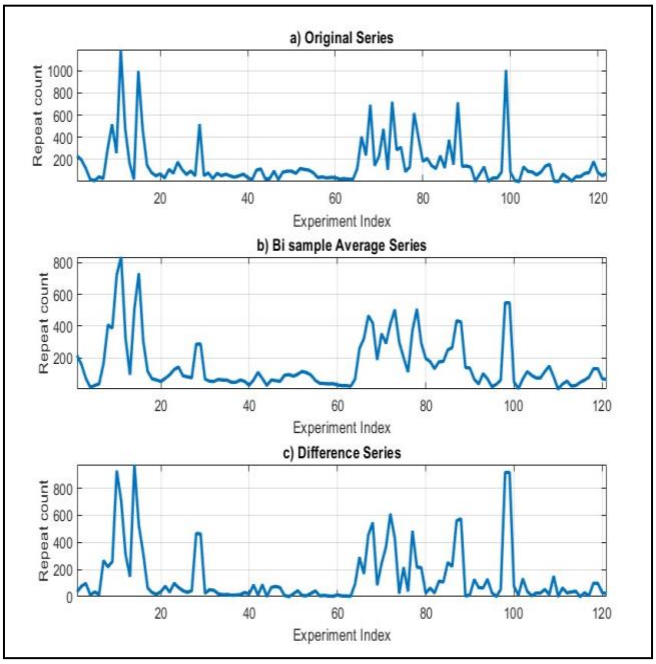

Figure 2. The inter failure duration series (a), along with the bi-sample mean (b) and absolute valued differenced series (c)

The original series, the output of the bi-sample mean process and the differencing can be seen in Fig. 2. The upper subplot is the original series. The second one is the averages and latter one being the differences series.

3. Frequency Impact

From the Fig.3, we can see that original series, shown with 'o' marks, has a rather flat frequency domain spectrum.

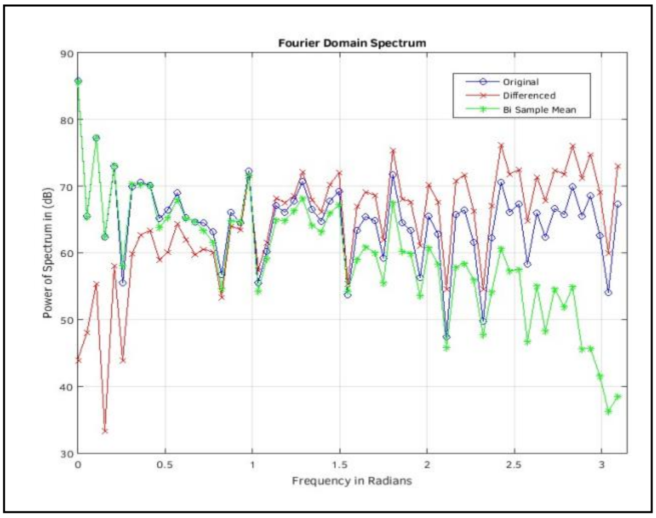

Figure 3. The observation series squared values in the Fourier frequency domain with 'o' for original series, the difference series is with 'x', and finally the bi-sample average series is marked with an asterisk '*'

The DC harmonics of the original are 15 dB stronger than those of the higher frequency components of the difference series. They are marked with 'x' marks. In this sense, the bi-sample average, shown by '*' marks, is removing some of the highest spectra impacting the power spectral density and autocorrelation outcome.

4. Discussion

A meaningful control is checking if the series at hand has persistent mean and variance within different limited time frames. It does not mean the series is stationary even if it has constant mean and variance but if it does not have such quality, it is not stationary (Parey et al. 2019; Muheialdin et al. 2014). This quality control can also be verified by a student-t test controlling μ and σ^2 is statistically different from overall values (Lee et al. 2008).

Differencing and averaging techniques aim to identify the hidden character that behaves stationary, yet is not directly apparent (James et al. 2011, Chambers et al. 1996). The differencing, if the series is monotonically increasing, alleviates the increments. It looks at the difference of samples, removing an immediate effect but revealing the hidden statistical character. With knowledge from signal processing about filtering, the bi-sample difference operation mostly removes low frequency components of the series. The Bi-sample Average takes the mean of two consecutive samples, removing the high frequency components from the signal. These effects are visible through Discrete Fourier Transform (DFT) or its rapid variant the Fast Fourier Transform (FFT) as available in Fig.3. These techniques can have an impact on μ parameter as well. Some studies investigate these mean adjustments (Presno et al. 2003).

The auto-correlation, variance and covariance are related and they are a part of the definition of the stationarity. Some of the tests try to identify if the homoscedasticity or heteroscedasticity exists in series or not for persisting variance character or dependence in a series (Chowdhury et al. 2017; Machiwal et al. 2008; Kipinski et al. 2011). Our observations indicate a shift to heteroscedasticity scenario as outcome of modifications.

Another method is to pre-filter these observations whence there exist seasonality (Taylor et al. 2003) Concentration in this study is to see what happens to knowledge in the signals, how the stationarity behaviors are affected along with the changes for bi-sample differencing and bi-sample averaging.

In Fig. 3, the low frequency terms are high for original and bi-sample average series. This could mean correlations with increasing lags are fading out, but also it tells the signals long-term lags are not similar to the early ones. There are parts more correlated and some parts that are less correlated, indicative of a weaker Independent Identical Distributed (IID) character. On the other hand, high frequency components or in other words short tern lags being similar is the case for the differenced sequence.

Seasonality is a trend persistent for a shorter time. The fact that it is uncommon that stationarity does not fail whence the trend is removed. As an outcome of observations in the series, cold days turn in higher and the warmer ones end up with the lower reliability indicating that the passive cooled device is susceptible to ambient air temperature. Once all trends are removed, this condition is sorted out as well. Bi-sample averaged series is resulting as non-stationary for both KPSS and ADF tests, contrary to all conditions yielding stationary outcomes for differenced series. This can be the case as local trends are more emphasized with bi-sample averaging technique.

The operations of differencing and averaging methods affect the series per useful qualities of predictions. A removed higher frequency component would, in some scenarios affect the variances. It means predictions for reliability estimates will change. On the other hand, if the Fig.1 presenting all three forms of the observation series is considered. In a comparison between all three, differencing technique removes the DC component of the series, which are useful for MTBF predictions.

With regard to Table 1, the μ and σ^2 stationarity with results of the differencing operations are granted per ADF and KPSS tests whereas Engel's heteroscedasticity test ends in the positive outcome for this quality. It means that the variance stationarity is affected negatively. With the difference interventions causing a deviation from the mean and variance could result in losing touch with simple known distributions like Exponential. The outcome of Engel's arch test indicates some concerns on this issue. On the other hand, if solely averaging based manipulations were performed, they could be misleading as well, hiding inconsistencies in events. The test results for averaging are not favorable in this case like the other method.

5. Conclusion

The DC term disappears after application of differencing technique. This is affecting the expectation (i.e. Mean) from the sequence and is a significant term for a probability prediction. The variance, considered as taking place along with high frequency components, is impacted by the averaging technique. This parameter is important also for making accurate probability estimates preventing higher costs to the producer or the consumer. It is interesting to note that the heteroscedasticity is observed after both of these operations. Such a finding indicates, the variance becoming time dependent.

The study tries to answer the research question: "what is the impact of differencing and bi-sample average on the reliability predictions like MTBF?". With observations on hand, MTBF and variance figures are impacted. The existing trends are erased by the differencing technique. The outliers as long success periods are lost at some level as outcome of averaging technique since high frequency findings are erased.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Effect of Temperature, Pressure and Humidity on Battery Consumption in Unmanned Aerial Vehicles

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Abstract

With the advancing technology, unmanned aerial vehicles (UAVs) have shown significant development. However, the battery technology has struggled to keep pace with these advancements, resulting in UAVs needing to efficiently manage their limited energy resources. Therefore, this study aims to examine factors that contribute to battery energy consumption beyond planned usage scenarios.
A quadcopter equipped with Pixhawk Holybro 4 flight controller was used in the study. It was tested under varying atmospheric conditions of air pressure, humidity, and temperature. The quadcopter performed automated flights, hovering at a height of 5 meters for 3 minutes, while the battery consumption was monitored. The study was conducted under real atmospheric conditions to simulate practical scenarios.
The research revealed that the examined factors significantly impact battery depletion. Specifically, temperature and humidity were observed to have a more pronounced effect on battery consumption compared to air pressure.

1. Introduction

The demand for unmanned aerial vehicles (UAVs) is increasing day by day due to the advancing technology, the production of lighter and more durable materials as a result of developments in material science, and the availability of electronic components at lower costs. Consequently, UAVs have begun to be used in many fields. Today, fixed-wing, rotary-wing, and VTOL UAVs, which possess the characteristics of both, are in use. Fixed-wing UAVs can fly long distances due to the lift generated by their wings and their high aerodynamic properties, but they cannot perform vertical take-offs and landings and require a runway for such operations. On the other hand, rotary-wing aircraft have the advantage of being able to perform vertical take-offs and landings and maneuver easily, but they have lower aerodynamic properties and shorter ranges. VTOL aircraft, however, incorporate the advantageous features of both models. Considering these advantages and disadvantages, these aircraft are used in various fields today. Especially, the ability of rotary-wing UAVs to perform vertical take-offs and landings and move rapidly has enabled many tasks to be accomplished quickly. They are increasingly used not only in military, reconnaissance, and photography applications but also in agriculture, healthcare, and cargo transportation.

Since UAVs operate in airspaces close to the ground, they are significantly affected by weather events. The primary weather events impacting UAVs include wind and rain, while factors such as air pressure and temperature also affect flight (Demircioglu & Basturk, 2017; Ercan et al., 2022). These effects cause the limited energy of the batteries that power UAVs to deplete more quickly (Ercan et al., 2024). Although it is not possible to completely mitigate the impact of such environmental conditions, efforts are being made to use the battery more efficiently (Bianchi et al., 2024; Yacef et al., 2017). In particular, studies focused on predicting energy consumption in advance have been conducted. For instance, Prasetia et al. (2019) proposed a black-box modeling approach to predict UAV energy consumption, achieving a prediction accuracy of 98.773%. In the studies conducted by Abeywickrama et al. (2018a) and Abeywickrama et al. (2018b), the factors affecting the UAV's battery were individually examined.

UAVs face various environmental challenges during their development and mission execution. There are many obstacles in our world that endanger UAV flights, and UAVs are also significantly affected by atmospheric weather events. One such effect is temperature, which dramatically impacts the flight characteristics, motor RPM, and battery discharge duration of UAVs. UAVs typically use lithium-ion and lithium-polymer batteries, which are known to perform inefficiently under extreme hot and cold conditions. A study by Li et al. (2021) found that at 60°C, the discharge capacity of these batteries significantly decreases, and the battery can even fail due to high temperatures. At temperatures below -25°C, UAVs were observed to malfunction. Furthermore, a literature review by Vidal et al. (2019) examined various issues related to lithium-based batteries in very low temperatures, including capacity loss, power loss, reduced lifespan, safety hazards, uneven capacity, charging difficulties, thermal management system complexity, battery model and state estimation complexity, and increased costs. These studies demonstrate that low temperatures adversely affect batteries in multiple ways.

Temperature, humidity, and air pressure have significant effects on air density, and consequently, on the thrust generated by an aircraft (Calva & Espino C., n.d.; Leal Iga et al., 2008). An increase in air pressure is known to increase air density. Higher air density allows propellers to generate more thrust at the same RPM, thereby reducing battery consumption. On the other hand, an increase in humidity decreases air density. In lower air density, at the same RPM, an UAV will generate lower thrust. As air temperature increases, the kinetic energy of air molecules increases, causing them to move more vigorously. This results in a less dense air and lower thrust generated by the UAV's propellers.

This study investigates the combined effects of humidity, temperature, and pressure on battery consumption under real-world weather conditions. Evaluating these parameters simultaneously in real-world conditions is crucial for making more accurate calculations, and this aspect is where the uniqueness of the study lies. While previous studies in the literature have focused on a single parameter, this study considers three different parameters and performs a correlation analysis between them.

2. Methodology

In this study, a Pixhawk Holybro 4 flight controller was used on a drone where battery consumption data was obtained. Flight tests were conducted at various altitudes above sea level. To ensure consistent conditions for measuring battery consumption, all tests were conducted in calm weather conditions, excluding factors like wind that could affect battery usage.

Flight tests were conducted at different air pressures, humidity levels, and temperatures, and battery consumption data was directly obtained from the flight controller's log records. The aircraft maintained a steady hover at 5 meters altitude for 3 minutes during automatic flight.

The battery consumption rates of interest in this study are related to the thrust generated by the UAV. As the thrust ratio increases, the battery consumption also increases. Thrust production is influenced by parameters such as temperature, humidity, and air pressure. Therefore, to examine battery consumption, these parameters need to be investigated. Equation (1) shows the formula for the thrust generated by the UAV propeller. Here, T(Newton) represents the thrust, C_T denotes the thrust coefficient, ρ(kg/m³) stands for air density, n represents the propeller rotational speed, and D (m) signifies the propeller diameter.

$$T = C_T.\rho.n^2.D^4 \tag{1}$$

Air pressure and ambient temperature affect air density. In Equation (2), air density ρ is directly proportional to air pressure P(Pascal), which is used to express pressure. As air pressure increases, the number of molecules per unit area increases, thus increasing density. Similarly, as shown for temperature T(Kelvin), as temperature increases, the number of molecules per unit area decreases, resulting in decreased density.

$$\rho = \frac{P}{R.T} \tag{2}$$

Another factor that affects air density is humidity. As the amount of water vapor in the air increases, air density decreases. Equation (3) illustrates the effect of humid air on density. P_d(Pa) represents the pressure of dry air, and P_v(Pa) represents the pressure of water vapor. When these values are calculated, the density of dry air is higher compared to humid air.

$$\rho = \frac{P_d}{R_d T} + \frac{P_v}{R_v T} \tag{3}$$

It is known that air density affects the thrust generated by UAVs. However, the specific effects of temperature, humidity, and air pressure—which influence air density—on UAV thrust and their subsequent impact on battery consumption are not well understood. Therefore, this study aims to investigate how each of these parameters individually affects battery consumption through their influence on thrust.

2.1. Components of UAV and Other Tools

In this study, a quadcopter UAV with four rotors was utilized, as depicted in Figure 1. The quadrotor used in this study features an X-configuration.

Figure 1. The quadcopter used in the study. (Ercan et al., 2024)

The quadcopter used in this study weighs 1760 grams. It features a F450 type frame with a diameter of 45 cm, equipped with four brushless motors, four 30A ESCs (Electronic Speed Controllers), a flight controller, telemetry system, and a remote-control receiver. The components of the UAV are detailed in Table 1.

Table 1. Components of UAV (10p)

Components	UAV
Frame	F450 Frame
Flight Controller	Holybro Pixhawk 4
Battery	6200 mAh Li-Po battery
Propeller	4 1045 propellers
Electronic Speed Controller	4 Emax 30A ESCs
Motors	4 brushless Motors Emax XA2212 980 kv

The UAV used in the study is equipped with a PID (Proportional-Integral-Derivative) algorithm for the flight controller, GPS (Global Positioning System), and automatic flight systems, enabling it to hover in place during flight.

A BMP180 sensor was used to measure pressure and temperature. An Arduino Uno microcontroller was utilized to read data from this sensor, as shown in Figure 2.

The Pixhawk Holybro 4 flight controller installed on the aircraft provides log data related to the battery. The remaining battery capacities were obtained using these data. The analyses and visualizations were conducted directly in the MATLAB environment, and the graphs were generated within the same application.

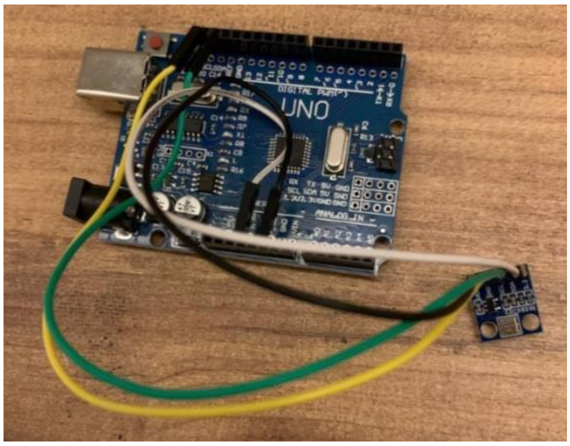


Figure 2. The BMP180 sensor for obtaining temperature, humidity, and atmospheric pressure data and the Arduino Uno microcontroller

3. Experimental Study

Flight tests were conducted under real atmospheric conditions with different temperatures, humidity levels, and air pressures. The battery consumption and atmospheric parameters for the quadcopter's first flight are shown in Figures 3A and 3B. At the end of 300 seconds, the quadcopter's battery level dropped to 44%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's second flight are shown in Figures 3C and 3D. At the end of 300 seconds, the quadcopter's battery level dropped to 48%, completing the flight.

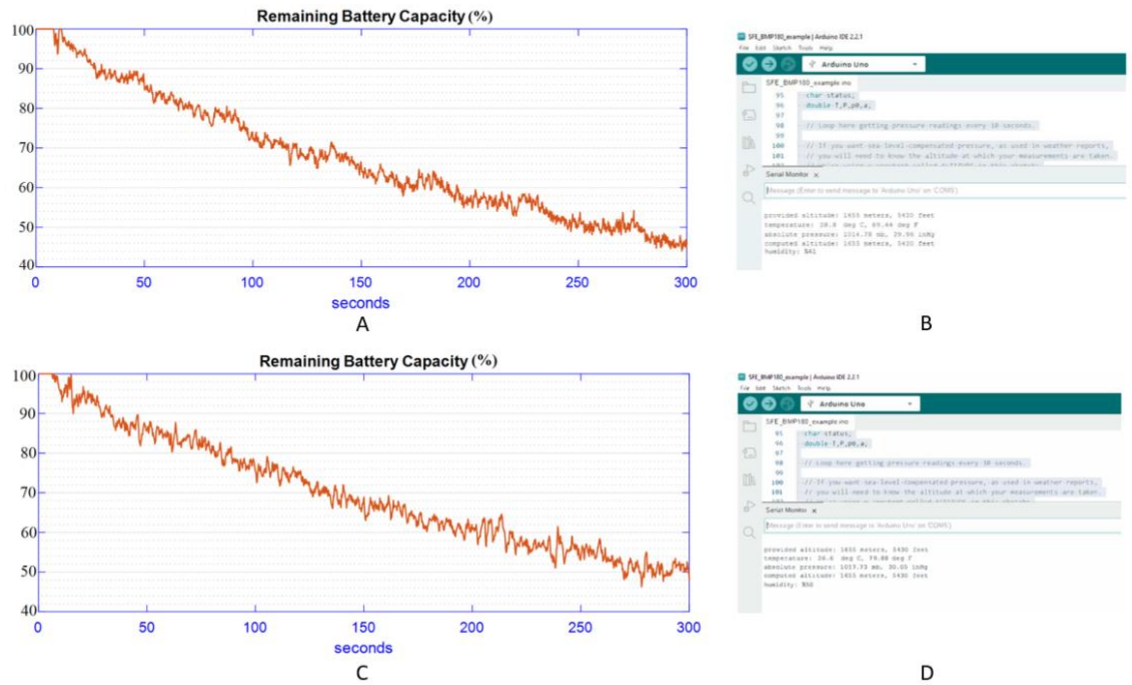


Figure 3. (A) Quadcopter's Battery Consumption During Flight At 20.8°C Temperature, 1014.78 Millibar Pressure, And 41% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 26.6°C temperature, 1017.73 millibar pressure, and 50% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's third flight are shown in Figures 4A and 4B. At the end of 300 seconds, the quadcopter's battery level dropped to 58%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's fourth flight are shown in Figure 4C and 4D. At the end of 300 seconds, the quadcopter's battery level dropped to 55%, completing the flight.

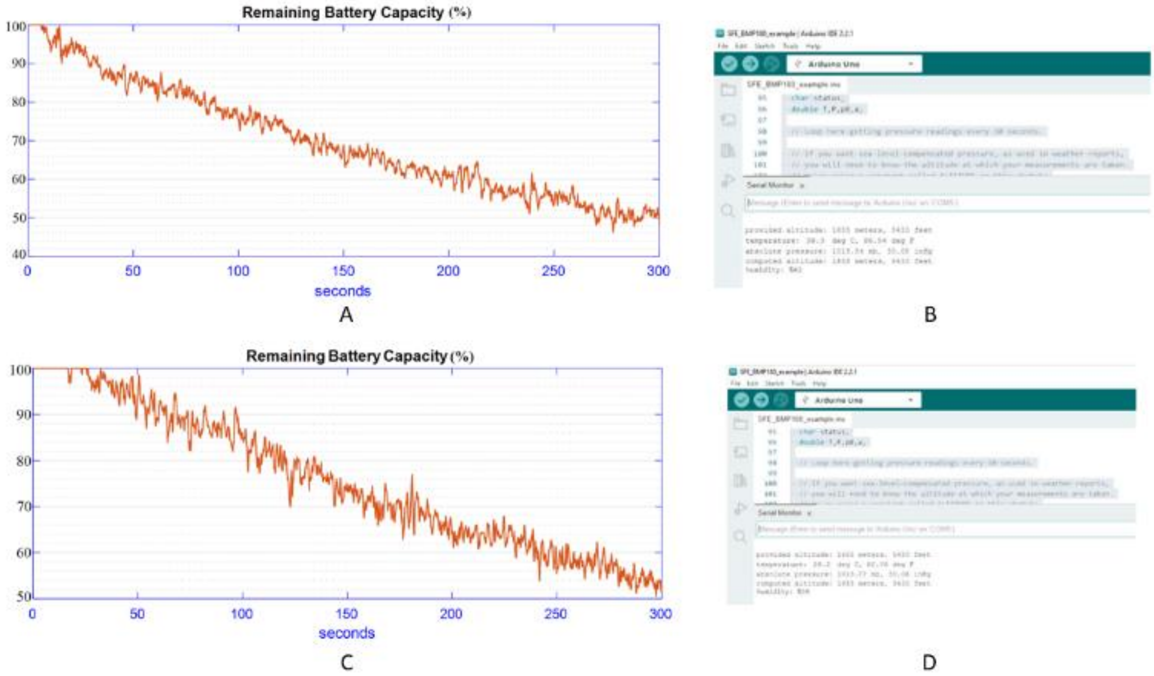


Figure 4. (A) Quadcopter's Battery Consumption During Flight At 30.3°C Temperature, 1018.84 Millibar Pressure, And 42% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 28.2°C temperature, 1018.77 millibar pressure, and 39% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's fifth flight are shown in Figures 5A and 5B. At the end of 300 seconds, the quadcopter's battery level dropped to 40%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's sixth flight are shown in Figures 5C and 5D. At the end of 300 seconds, the quadcopter's battery level dropped to 56%, completing the flight.

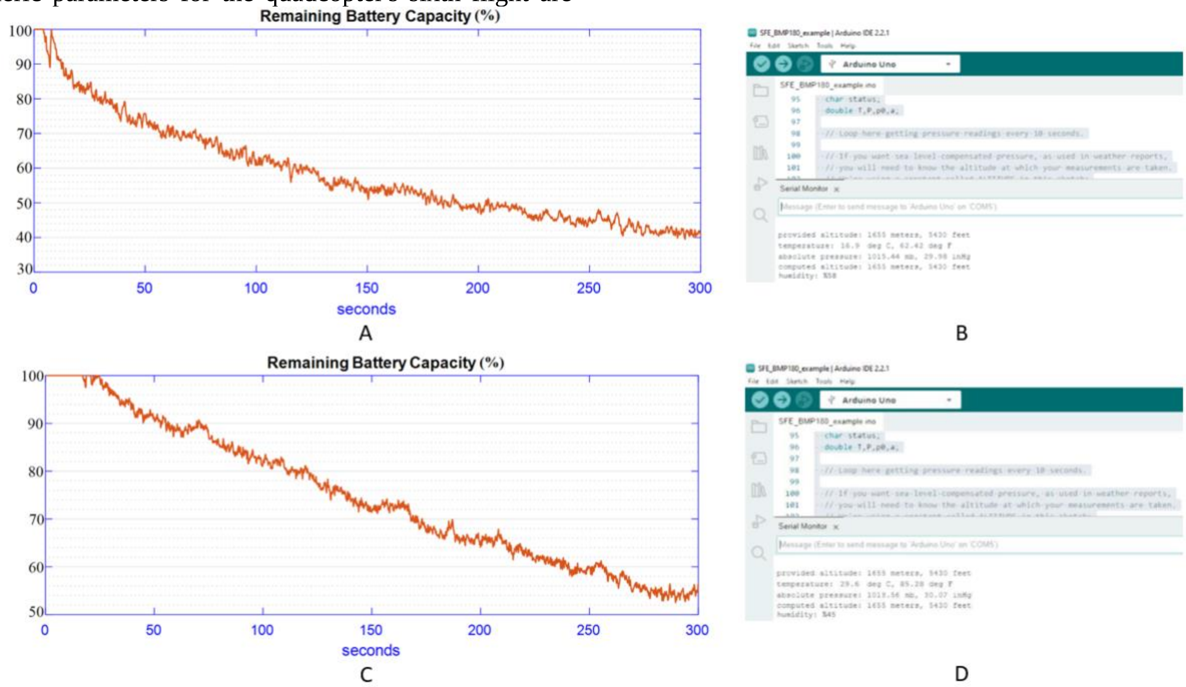


Figure 5. (A) Quadcopter's battery consumption during flight at 16.9°C temperature, 1015.44 millibar pressure, and 58% humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 29.6°C temperature, 1018.66 millibar pressure, and 45% humidity, (D) atmospheric parameters of (C).

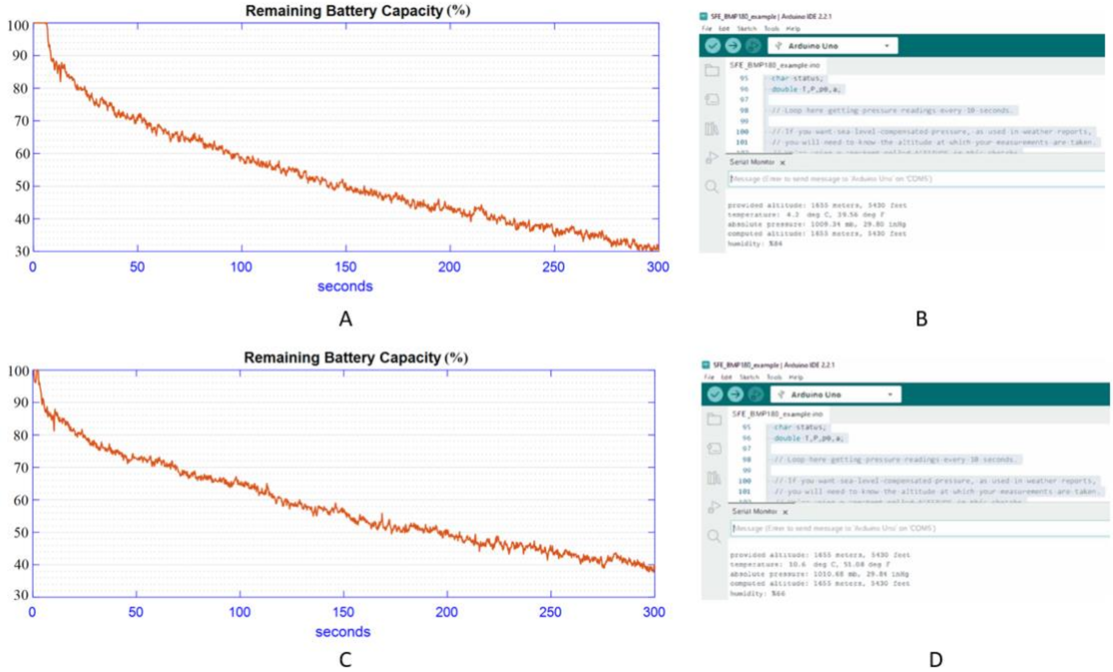


Figure 6. (A) Quadcopter's Battery Consumption During Flight At 4.2°C Temperature, 1009.34 Millibar Pressure, And 84% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 10.6°C temperature, 1010.68 millibar pressure, and 66% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's ninth flight are shown in Figures 7A and 7B. At the end of 300 seconds, the quadcopter's battery level dropped to 46%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's tenth flight are shown in Figures 7C and 7D. At the end of 300 seconds, the quadcopter's battery level dropped to 50%, completing the flight.

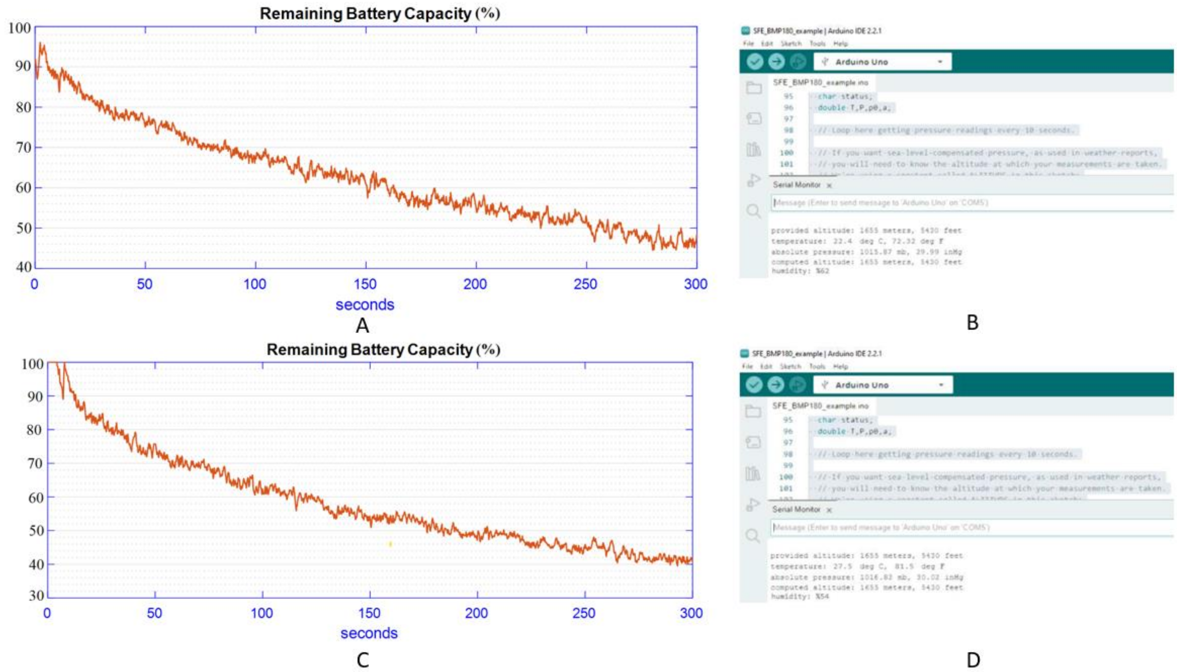


Figure 7. (A) Quadcopter's Battery Consumption During Flight At 22.4°C Temperature, 1015.87 Millibar Pressure, And 62% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 27.5°C temperature, 1016.82 millibar pressure, and 54% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's eleventh flight are shown in Figures 8A and 8B. At the end of 300 seconds, the quadcopter's battery level dropped to 35%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's twelfth flight are shown in Figures 8C and 8D. At the end of 300 seconds, the quadcopter's battery level dropped to 42%, completing the flight.

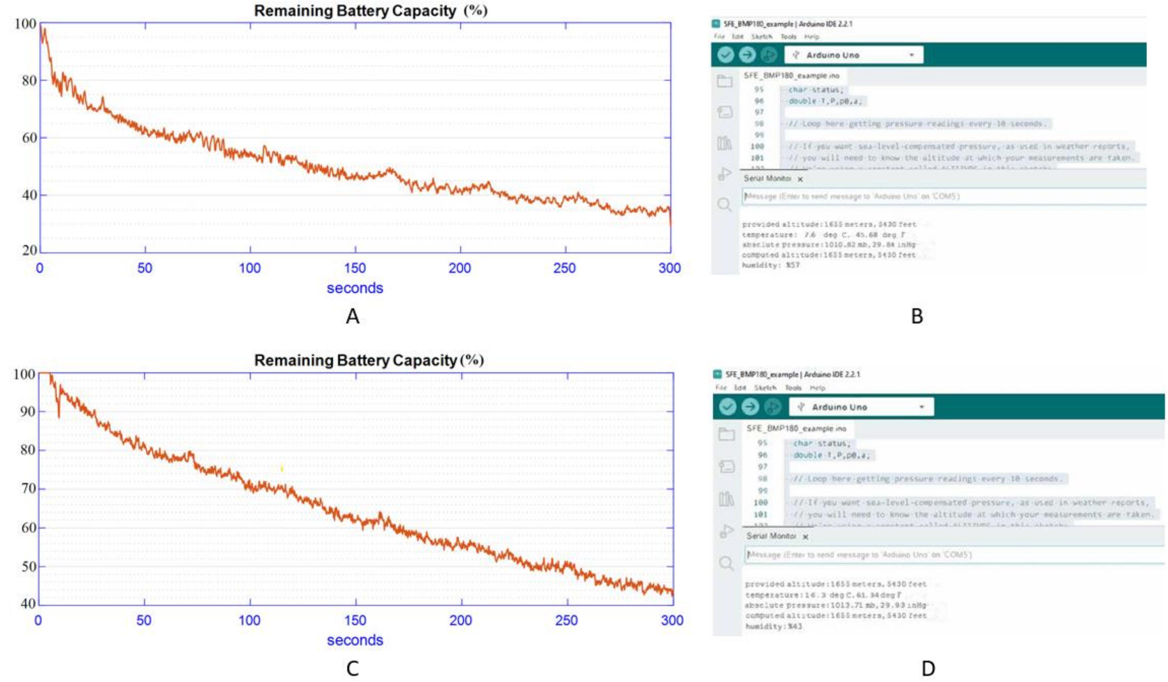


Figure 8. (A) Quadcopter's Battery Consumption During Flight At 7.6°C Temperature, 1010.82 Millibar Pressure, And 57% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 16.3°C temperature, 1013.71 millibar pressure, and 43% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's thirteenth flight are shown in Figure 9B. At the end of 300 seconds, the quadcopter's battery level dropped to 43%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's fourteenth flight are shown in Figures 9C and 9D. At the end of 300 seconds, the quadcopter's battery level dropped to 52%, completing the flight.

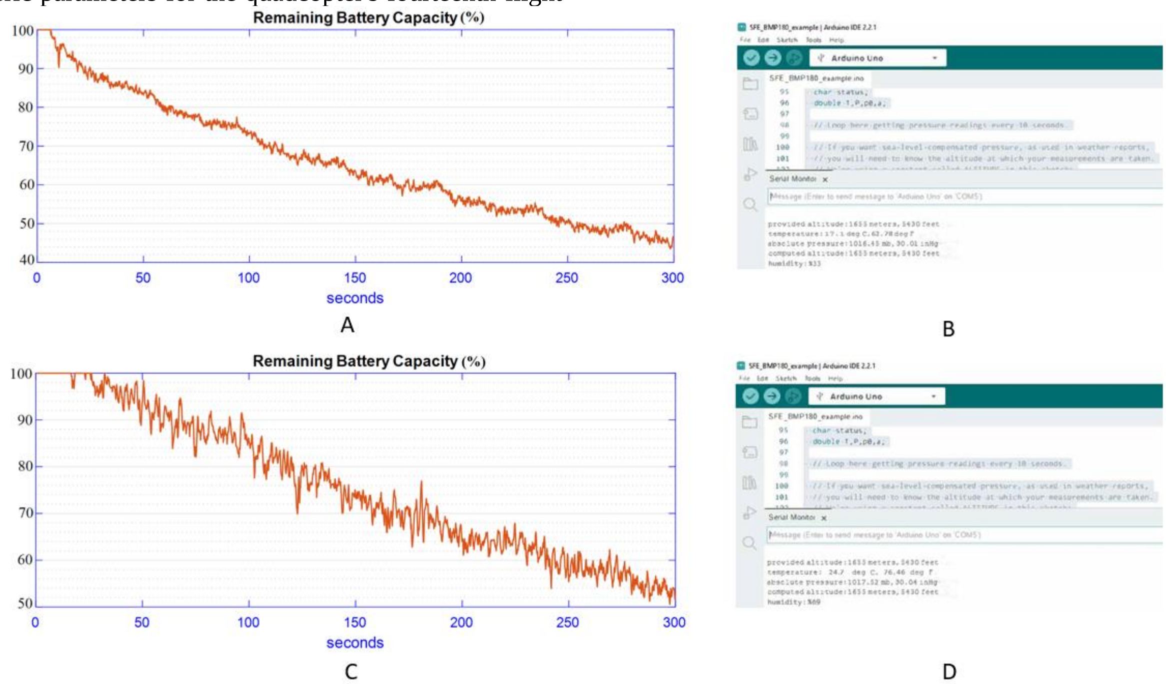


Figure 9. (A) Quadcopter's Battery Consumption During Flight At 17.1°C Temperature, 1016.45 Millibar Pressure, And 33% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 24.7°C temperature, 1017.52 millibar pressure, and 69% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's fifteenth flight are shown in Figures 10A and 10B. At the end of 300 seconds, the quadcopter's battery level dropped to 49%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's sixteenth flight are shown in Figure 15. At the end of 300 seconds, the quadcopter's battery level dropped to 36%, completing the flight.

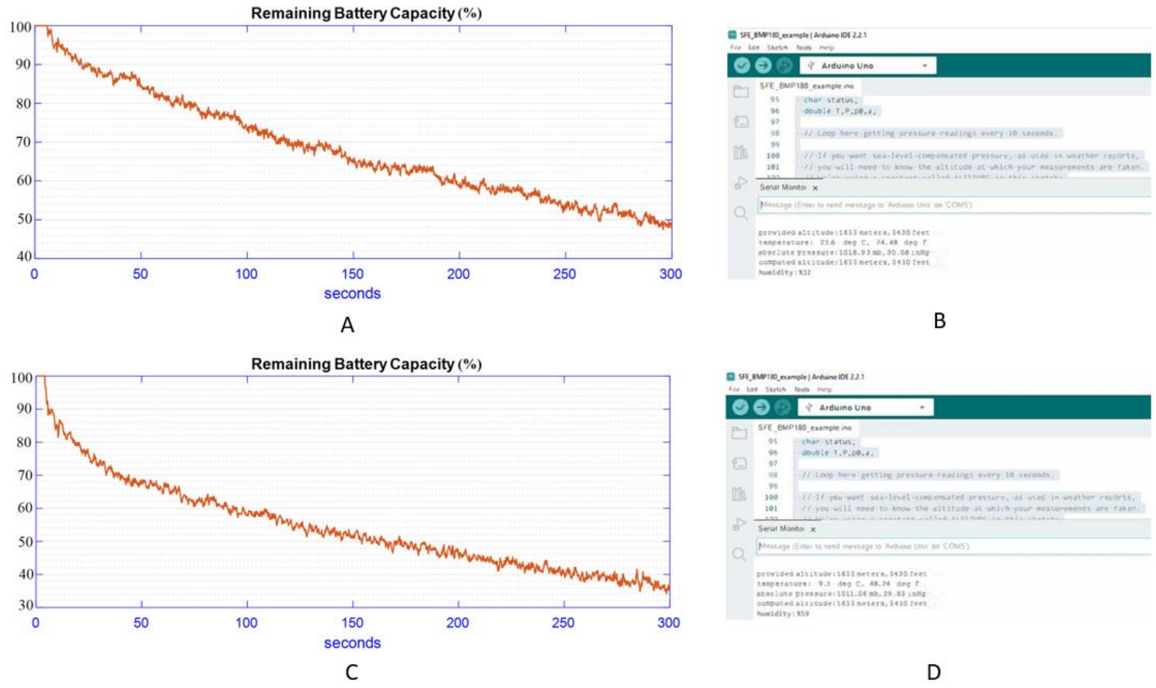
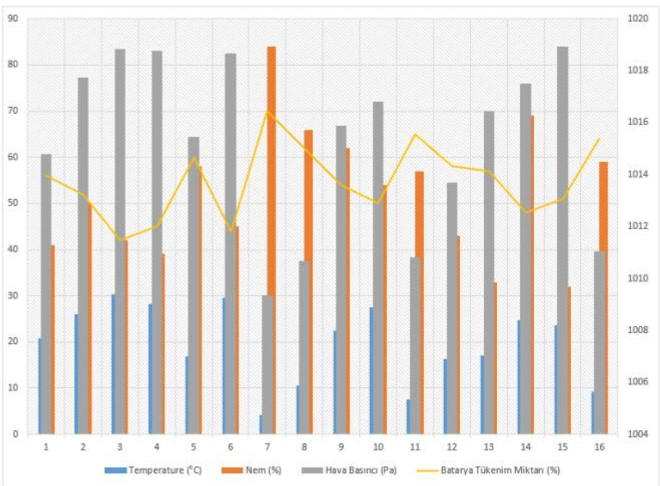


Figure 10. (A) Quadcopter's Battery Consumption During Flight At 23.6°C Temperature, 1018.93 Millibar Pressure, And 32% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 9.3°C temperature, 1011.06 millibar pressure, and 59% humidity, (D) atmospheric parameters of (C).

Figure 11 shows all battery consumption amounts.



***Units for temperature, humidity, and battery depletion are presented on the left axis, while units for air pressure are displayed on the right axis.**

Figure 11. All battery consumption amounts according to temperature, humidity, and air pressure.

4. Conclusion

The known effects of air pressure, humidity, and temperature on air density directly impact motor thrust, thereby affecting battery consumption. In this study, conducted to quantify these effects under real conditions, battery consumption varied by 42% to 64% across different weather conditions. Particularly, it was observed that battery consumption significantly increased in conditions of low temperature, low air pressure, and high humidity. Upon examining Figure 11, it was observed that humidity levels had a significantly greater impact on battery consumption. Additionally, when separate correlation analyses were conducted for these three data sets, the correlation coefficients were determined as follows:

-Temperature and Battery Depletion Rate: $r_{SB} \approx -0.876$ (strong negative correlation).
-Air Pressure and Battery Depletion Rate: $r_{HB} \approx -0.482$ (weak negative correlation).
-Temperature and Air Pressure: $r_{SH} \approx -0.204$ (weak negative correlation).

There is a strong negative relationship between temperature and battery depletion rate, indicating that as the temperature increases, the rate of battery depletion decreases. There is a weak negative relationship between air pressure and battery depletion rate, suggesting that air pressure does not significantly affect the battery's depletion rate. A weak negative relationship is also observed between temperature and air pressure, indicating that these two variables do not significantly influence each other.

The 22% variance in battery energy represents a substantial amount for UAV missions previously planned, potentially leading to mission failure.

Given the increasing integration of UAVs into everyday life in the coming years, it is crucial to consider temperature, humidity, and air pressure when planning battery usage. This study serves as a valuable resource for future research on how these environmental factors impact UAV operations.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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UAV Selection Using Fuzzy AHP and PROMETHEE Method

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Abstract

UAV (Unmanned Aerial Vehicle) is an aircraft that can fly by remote control or automated system and does not have the capacity to carry people. The optimal selection of UAVs is critical for the successful conduct of operations and the prevention of loss of life and property. The aim of this study is to prioritize the criteria affecting the selection of UAVs and to rank the Strategic UAVs based on these criteria. Thus, it is aimed to improve the UAV selection process of decision makers. As a result of the literature search, there were no studies on the most important criteria affecting the selection of operational, tactical and strategic UAVs. Therefore, Fuzzy AHP and PROMETHEE methods were applied to fulfill these objectives. As a result, it was determined that the most important criteria in the selection of UAVs are realizability, flight stability and payload success rate value.

1. Introduction

UAVs represent a class of unmanned, remotely controlled electro-mechanical flying devices characterized by autonomous or semi-autonomous operation (Mekdad et al. 2023). These vehicles, which vary in take-off weights and dimensions, are generally divided into three different groups as fixed-wing, rotary-wing and hybrid designs according to their rotor configurations (Elmeseiry, Alshaer, and Ismail 2021). UAVs are widely used in military fields due to their critical role in defense technology (Chaturvedi et al. 2019). The use of UAVs in surveillance, tactical reconnaissance and combat operations is becoming increasingly widespread due to their durability, low risk and cost-effectiveness (Hamurcu and Eren 2020). In addition to their single use, UAVs are increasingly used in swarms due to their many advantages (Erkec and Hajiyev 2020). The ability to visit different regions in different conditions is one of the most significant features of UAV (Tadić et al. 2024). UAVs also play important roles in firefighting; avalanche rescue and logistic support missions where traditional methods face difficulties caused by geographical constraints and adverse weather conditions (Mohd Noor, Abdullah, and Hashim 2018). UAVs are now smaller, faster, more competent, more precise, and more dependable than they were in the past due to a combination of rapid developments and technological advancements (Keleş 2024). Although UAVs were first created for military purposes, a wide range of civilian applications have recently surfaced, greatly expanding UAV capabilities at a lower cost (Wang et al. 2023).

As a result of research, Hamurcu and Eren (2020) emphasized the need for a systematic and effective approach for the selection of UAVs. This study proposes an integrated method based on analytical hierarchy process (AHP) and ranking by similarity to ideal solution (TOPSIS) methods, which are multi-criteria decision-making methods. With the use of these methods, UAV alternatives are effectively evaluated in the selection process (Hamurcu and Eren 2020). In Uçar, Adem, and Tanyeri (2022) study, the ideal engine selection problem for UAVs is focused and a solution is proposed for this problem using the Analytic Hierarchy Process (AHP) method. This is the first paper in the literature to address this problem and apply the AHP method to this problem. Furthermore, the proposed mechanism provides a decision support system for UAV manufacturers and users. This system is intended to help UAV users make the right choices by enabling them to evaluate the appropriate brand among performance and different criteria (Uçar, Adem, and Tanyeri 2022). In Ardil (2023) study, it is aimed to determine the most suitable UAV by considering various criteria. For this purpose, standard fuzzy set methodology and decision makers' selection criteria are used. A practical numerical example is presented to demonstrate the applicability of the proposed approach. A comparison was made between UAVs with different missions

and the most suitable vehicle was selected (Ardil 2023). In Dagdeviren's study, an integrated approach for multi-criteria equipment selection was proposed and implemented using Analytic Hierarchy Process (AHP) and Preference Ranking Organization Method (PROMETHEE). The proposed method includes steps such as analyzing the equipment selection problem, determining the weights of the criteria and making the final ranking. The decision approach presented in this study involves the use of AHP and PROMETHEE combined decision-making methods to solve equipment selection problems (Dağdeviren 2008).
Therefore, the correct selection of UAVs is important for the successful completion of operations. The aim of this study is to prioritize the criteria affecting the selection of strategic UAVs and to rank the UAVs based on these criteria. Thus, it is aimed to improve the strategic UAV selection process and to help decision makers.

2. Methodology

2.1. Fuzzy AHP

Fuzzy AHP is a method used for decision-making processes in UAV selection by incorporating uncertainty (Sadiq and Tesfamariam 2009). The determination of criteria weights and values under fuzzy logic is the basis of this method. In this way, more effective results are obtained in complex and uncertain decision-making processes. Firstly, the matrix in Equation 1 is created as the numerical equivalent of the experts' evaluations.

$$A = [1\ \alpha_{12} \cdots \alpha_{1n}\ \alpha_{21}\ 1 \cdots \alpha_{2n} \vdots \vdots \ddots \vdots\ \alpha_{n1}\ \alpha_{n2} \cdots 1\ ] \tag{1}$$

1. Journal of Aviation, Journal of Aviation. Journal of Matrix A is reciprocal, if $\alpha_{ij} = 1 / \alpha_{ij}$ for each $1 \leq i,j \leq n.$
2. Matrix A is consistent if $\alpha_{ij} \cdot \alpha_{jk} = \alpha_{ik}$ for each $1 \leq i,j,k \leq n.$
3. If the condition in Case 2 is not valid, we can say that A is inconsistent.

In the classical AHP method, the consistency of A is measured by the consistency index (CI). In Equation 2, CI is calculated as follows (Ramík and Korviny 2010):

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{2}$$

The consistency of the decision is checked using the formula CR= CI / RI. RI values include the random consistency index listed in Table 1.

Table 1. Random consistency index

Matrix Size	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Random consistency index (RI)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The following procedure was used to measure the consistency of the matrices in Equation 3 (Sadiq and Tesfamariam 2009):

$$NI_n^{\sigma}(\hat{A}) = \gamma_n^{\sigma} \cdot max_{i,j}\left\{max\left\{\left|\frac{w_i^L}{w_i^U} - a_{ij}^L\right|, \left|\frac{w_i^M}{w_i^M} - a_{ij}^M\right|, \left|\frac{w_i^U}{w_i^L} - a_{ij}^U\right|\right\}\right\}$$

where

$$\gamma_n^{\sigma} \cdot = \{\frac{1}{max\left\{\sigma - \sigma^{(2-\frac{2n}{n}}, \sigma^2\left\{\left(\frac{2}{n}\right)^{\frac{2}{n-2}} - \left(\frac{2}{n}\right)^{\frac{n}{n-2}}\right\}\right\}}\ \frac{1}{ax\left\{\sigma - \sigma^{\left(2-\frac{2n}{n}\right)}, \sigma^2 - \sigma\right\}} \quad otherwise. \tag{3}$$

While the index values are between 0 and 1, a value of 0 indicates that the matrix is completely consistent. Then, the triangular fuzzy numbers, which are the elements of the matrix, are treated with a pairwise comparison matrix. A triangular fuzzy number a is expressed by a triplet of natural numbers:

$$\tilde{A} = \left((a_{11}^L; a_{11}^M; a_{11}^U) \cdots (a_{1n}^L; a_{1n}^M; a_{1n}^U) \vdots \ddots \vdots\ (a_{m1}^L; a_{m1}^M; a_{m1}^U) \cdots (a_{mn}^L; a_{mn}^M; a_{mn}^U)\right) \tag{4}$$

In particular, let Ã be an n × n matrix with triangular fuzzy elements. We say that A is reciprocal if the following condition is satisfied (Equation 5)

$$\hat{a}_{ij} = (a_{ij}^L; a_{ij}^M; a_{ij}^U)\ implies\ \hat{a}_{ij} = \left(\frac{1}{a_{ij}^U}; \frac{1}{a_{ij}^M}; \frac{1}{a_{ij}^L}\right)\ for\ all\ i,j = 1,2,\ldots,n \tag{5}$$

As in classical AHP, interval scale is used. The range of this scale is {1/9,1/8...,1/2,1, 2,...,8,9}.

Table 2. Linguistic variables

Linguistic Judgement	Value	Triangular Fuzzy Number	Inverse Triangular Fuzzy Correspondence
Equally Important	1	1, 1, 1	1, 1, 1
Medium Important	3	2, 3, 4	1/4, 1/3, 1/2
Strongly Significant	5	4, 5, 6	1/6, 1/5, 1/4
Very Strongly Important	7	6, 7, 8	1/8, 1/7, 1/6
Extremely Important	9	8, 9, 9	1/9, 1/9, 1/8

Fuzzy weights, $w_k = (w_k^L, w_k^M, w_k^U), k = 1,2,\dots,n$ is obtained by utilising Equation 6-8 (Pavel and Talašová 2016):

$$C_{min} = \left\{ \frac{\left(\prod_{j=1}^{n} a_{ij}^{M}\right)^{1/n}}{\left(\prod_{j=1}^{n} a_{ij}^{L}\right)^{1/n}} \right\} \text{ while } w_k^L = C_{min} \cdot \frac{\left(\prod_{j=1}^{n} a_{kj}^{L}\right)^{1/n}}{\left(\prod_{j=1}^{n} a_{kj}^{M}\right)^{1/n}}, \tag{6}$$

$$w_k^M = \frac{\left(\prod_{j=1}^{n} a_{kj}^{M}\right)^{1/n}}{\left(\prod_{j=1}^{n} a_{ij}^{M}\right)^{1/n}}, \tag{7}$$

$$C_{max} = \left\{ \frac{\left(\prod_{j=1}^{n} a_{ij}^{M}\right)^{1/n}}{\left(\prod_{j=1}^{n} a_{ij}^{U}\right)^{1/n}} \right\} \text{ while } w_k^L = C_{min} \cdot \frac{\left(\prod_{j=1}^{n} a_{kj}^{U}\right)^{1/n}}{\left(\prod_{j=1}^{n} a_{kj}^{M}\right)^{1/n}}, \tag{8}$$

2.2. PROMETHEE

PROMETHEE method is used for comparing and ranking different alternatives. PROMETHEE evaluates the performance of UAVs according to specified criteria and determines the advantages and disadvantages of each UAV over the others.

$$max\{f_1(a), f_2(a), \dots, f_n(a) | a \in A| \} \tag{9}$$

Here A is a finite set of possible alternatives and fj denotes the n criteria to be maximized (Equation 9). For each alternative, fj(a) is an evaluation of this alternative. When comparing two alternatives a,b ϵ A, the outcome of these comparisons is expressed in terms of preference (Equation 10). Therefore, P is a preference function. The difference criterion between the evaluations of two alternatives (a and b) with respect to a given alternative becomes a preference function ranging from 0 to 1 (Equation 11).

$$P_{j(a,b)} = G_j\left[f_j(a) - f_j(b)\right], \tag{10}$$

$$0 \le P_{j(a,b)} \le 1, \tag{11}$$

Let fj(i) be the preference function associated with criterion i, where Gj is a non-decreasing function of the observed deviation (d) between fj(a) and fj(b) (Equation 10). PROMETHEE requires the calculation of the following values for each alternative a and b (Equations 12-15):

$$\pi(a,b) = \frac{\sum_{j=1}^{n} \omega_j P_{j(a,b)}}{\sum_{j=1}^{n} \omega_j}, \tag{12}$$

$$\phi^+(a) = \sum_{x \in A} \pi(a,x), \tag{13}$$

$$\phi^-(a) = \sum_{x \in A} \pi(a,x), \tag{14}$$

$$\phi(a) = \phi^+(a) - \phi^-(a) \tag{15}$$

For each alternative a belonging to the set of alternatives A, π (a, b) is the overall preference index of a with respect to b (Equation 12). $\phi^+(a)$ The outflow expresses how a dominates all other alternatives of A (Equation 13). Symmetrically, the input flow $\phi^-(a)$, expresses how a is dominated by all other alternatives of A (Equation 14). ϕ(a) is called the net flow (Equation 15).

3. Findings

3.1. Determination of Criteria

The criteria considered in the selection of strategic UAVs play a critical role in the decision-making process. Based on the recommendations of experts, it has been determined that 9 criteria are decisive in the selection of Strategic UAVs. Table 3 shows these criteria.

Table 3. UAV selection criteria

Code	Criteria
D1	Maximum Take-off Weight
D2	Range
D3	Cost per Hour
D4	Fuel Capacity
D5	Success Rate Value of Load
D6	Maintenance and Repair Requirement
D7	Spare Parts Supply
D8	Realizability
D9	Flight Stability

An explanation of why these criteria are important in UAV selection is given below:

Range refers to the maximum distance the UAV can cover during a single operation and is important for operational flexibility. The cost per hour provides an hourly calculation of the UAV's operation and maintenance costs and helps to evaluate its long-term cost-effectiveness. Fuel capacity determines the amount of fuel that the UAV can carry for the maximum duration and distance that it can fly in a single flight. The payload success rate value expresses the relationship between the amount of payload the UAV can carry and its success rate and determines the importance in completing the mission. Maintenance and repair requirements determines the need for regular maintenance and repair of the UAV and is an important factor affecting operational efficiency. Spare parts procurement ensures that the spare parts required for the UAV to be continuously operational are provided in a timely and appropriate manner. Realizability refers to the ability of the UAV to be produced and developed on site, to meet operational requirements and to be used effectively in real-world conditions. Flight stability refers to the UAV's ability to remain in the air in a stable manner and to successfully perform targeted flights. The values of these criteria on UAVs are shown in the table below (Table 4)

Table 4. Criteria values of strategic UAVs

Alternatives	D1	D2	D3	D4	D5	D6	D7	D8	D9
SUAV1	3300	6500	1278	5000	0.62	0.40	0.70	0.76	0.61
SUAV2	25000	6000	2290	6500	0.76	0.27	0.79	0.43	0.53
SUAV3	20215	4100	3289	3640	0.74	0.39	0.66	0.65	0.43
SUAV4	4200	4000	3800	4782	0.42	0.42	0.74	0.86	0.45
OUAV1	3250	200	1303	3161	0.42	0.24	0.50	0.63	0.22
OUAV2	6000	1000	3573	3296	0.63	0.44	0.59	0.92	0.70
OUAV3	20200	930	2198	7257	0.89	0.32	0.59	0.65	0.45
OUAV4	1633	2575	1050	1081	0.53	0.50	0.39	0.54	0.61
TUAV1	8255	2500	1636	4600	0.79	0.45	0.69	0.46	0.81
TUAV2	21315	3850	5686	8300	0.57	0.69	0.88	0.36	0.42
TUAV3	4860	1852	3500	1800	0.46	0.23	0.66	0.72	0.34
TUAV4	720	3700	1250	300	0.61	0.31	0.53	0.94	0.78

3.2. Creation of Fuzzy Matrix

The experts were asked to compare the 9 Strategic UAV criteria with each other. These experts consisted of academicians and field experts working on UAVs.

Table 5. Comparative fuzzy matrix (average)

	D1	D2	D3	D4	D5	D6	D7	D8	D9
		0.488	2.491	1.149	0.218	0.574	0.574	0.201	0.218
D1	1 1 1	0.582	3.160	1.380	0.281	0.803	0.803	0.254	0.281
		0.715	3.776	1.683	0.401	1.149	1.149	0.349	0.401
	1.398		2.491	2.000	0.330	1.149	0.660	0.280	0.435
D2	1.719	1 1 1	3.160	2.667	0.415	1.380	0.859	0.339	0.517
	2.048		3.776	3.288	0.574	1.644	1.149	0.435	0.660
	0.265	0.265		0.574	0.265	0.530	0.530	0.185	0.196
D3	0.316	0.316	1 1 1	0.678	0.316	0.582	0.582	0.229	0.242
	0.401	0.401		0.803	0.401	0.660	0.660	0.304	0.330
	0.597	0.305	1.246		0.244	0.530	0.561	0.244	0.175
D4	0.725	0.375	1.476	1 1 1	0.281	0.582	0.644	0.281	0.214
	0.871	0.500	1.741		0.349	0.660	0.758	0.349	0.280
	2.491	1.741	2.491	2.862		2.169	1.398	0.758	0.660
D5	3.554	2.408	3.160	3.554	1 1 1	2.853	1.745	1.000	0.803
	4.595	3.031	3.776	4.095		3.482	2.048	1.320	1.000
	0.871	0.611	1.516	1.516	0.287		0.758	0.218	0.287
D6	1.246	0.725	1.719	1.719	0.351	1 1 1	0.889	0.281	0.351
	1.741	0.871	1.888	1.888	0.461		1.084	0.401	0.461
	0.871	0.871	1.516	1.320	0.488	0.922		0.379	0.287
D7	1.246	1.165	1.719	1.552	0.573	1.125	1 1 1	0.437	0.351
	1.741	1.516	1.888	1.783	0.715	1.320		0.530	0.461
	2.862	2.297	3.288	2.862	0.758	2.491	1.888		0.871
D8	3.936	2.954	4.360	3.554	1.000	3.554	2.290	1 1 1	1.000
	4.983	3.565	5.404	4.095	1.320	4.595	2.639		1.149
	2.491	1.516	3.288	3.565	1.000	2.169	2.169	0.871	
D9	3.554	1.933	4.384	4.663	1.246	2.853	2.853	1.000	1 1 1
	4.595	2.297	5.335	5.724	1.516	3.482	3.482	1.149	

Table 5 shows the comparative fuzzy matrix obtained by taking the geometric mean of the experts' evaluations.

3.3. Determination of Weights

The weights obtained from the fuzzy comparison matrix are shown in Figure 1. Accordingly. it is determined that the most important criterion for strategic UAV selection is the realizability criterion (D8). while the second and third most important criteria are flight stability (D9) and payload success value (D5), respectively.

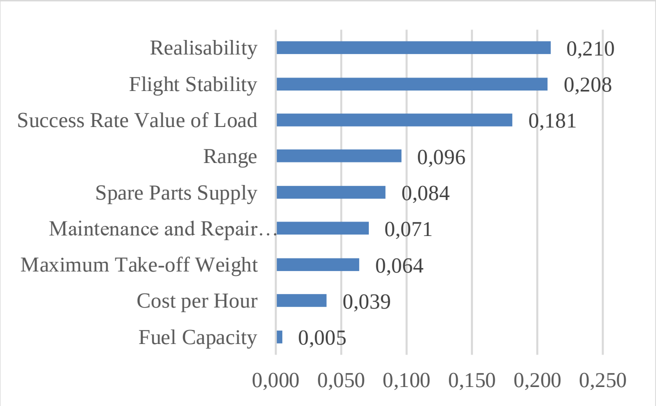

Figure 1. Ranking of UAV selection criteria

The reason why the most important criterion of UAV selection is the realizability criterion is to ensure mission continuity. Even if all other sub-criteria are positive in UAV operations, negative results in the realization of the flight and mission not only affect the entire UAV operation but also cause waste of effort (Erkec and Hajiyev 2020).

Table 6. Promethee flows (SUAV)

	ϕ^+	ϕ^-	ϕ net	Ranking
SUAV1	0.374	0.155	0.219	1
SUAV2	0.393	0.201	0.192	2
SUAV3	0.156	0.325	-0.169	3
SUAV4	0.161	0.402	-0.242	4

Table 6 shows the PROMETHEE flows. Accordingly, it is determined that the Strategic UAV with the highest net flow is SUAV1. Accordingly, it is determined that SUAV1 is the strategic UAV with the highest net flow. The reason for the selection of SUAV1 as the best strategic UAV is that it has significantly better performance in the range and cost per hour criteria compared to other strategic UAVs.

Table 7. Promethee flows (TUAV)

	ϕ^+	ϕ^-	ϕ **net**	**Ranking**
TUAV1	0.344	0.179	0.166	2
TUAV2	0.205	0.368	-0.163	3
TUAV3	0.135	0.408	-0.273	4
TUAV4	0.402	0.132	0.270	1

Table 7 shows the PROMETHEE flows. Accordingly, it is determined that the tactical UAV with the highest net flow is TUAV4. The reason for the selection of TUAV4 as the best tactical UAV is that it has significantly better performance in the range and realizability criteria compared to other tactical UAVs.

Table 8. Promethee flows (OUAV)

	ϕ^+	ϕ^-	ϕ **net**	**Ranking**
OUAV1	0.099	0.424	-0.325	4
OUAV2	0.399	0.132	0.266	1
OUAV3	0.344	0.149	0.195	2
OUAV4	0.188	0.325	-0.137	3

Table 8 shows the PROMETHEE flows. Accordingly, it is determined that the operational UAV with the highest net flow is OUAV1. The reason for the selection of OUAV1 as the best operational UAV is that it has significantly better performance in the realizability criterion compared to other operational UAVs.

4. Conclusion

In this study, the criteria affecting the selection of UAVs were identified, the importance of these criteria for UAVs was determined, and then the UAVs were ranked by making a sample application with the effect of these criteria. Accordingly, it was determined that the most important criteria in UAV selection are realizability, flight stability and success rate value of the payload. The least important criterion was determined to be fuel capacity. This study may contribute to improving and accelerate the decision-making process of decision makers when selecting a UAV.

The reason why range and cost-per-hour criteria stand out in strategic UAV selection is that long range increases operational effectiveness by covering large geographical areas, while low cost-per-hour reduces the total cost of operations and ensures financial sustainability. Long range increases operational flexibility by requiring less refueling and maintenance, while low cost allows for more and wider missions.

For tactical UAVs, range and realizability criteria are important as they enable effectiveness in short- and medium-range missions. Range extends the UAV's mission area, while realizability indicates its ability to be deployed quickly and flexibly. In tactical operations, these criteria assess the UAV's ability to adapt to different scenarios and perform various missions quickly and efficiently. In addition, it increases operational continuity and provides logistical advantages by working smoothly in maintenance and support processes.

In operational UAVs, the realizability criterion refers to the ability to perform various missions (intelligence, surveillance, reconnaissance, target designation) effectively and efficiently. This criterion is critical for the UAV's ability to respond quickly and adapt to different and emergency situations. Realizability refers to the UAV's reliability, low maintenance requirements and durability in long-term and uninterrupted operations. It also optimizes operational costs and resource utilization, enabling missions to be performed economically and efficiently.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Impact of Aspect Ratio on Structural Integrity and Aerodynamic Performance in Fixed-Wing UAV

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Abstract

This research is a systematic investigation of the effect of aspect ratio on the structural integrity and aerodynamic performance of fixed-wing unmanned aerial vehicles (UAVs). Higher aspect ratios are generally associated with greater aerodynamic efficiency, primarily through improved lift-to-drag (L/D) ratios, which are essential for extending flight endurance and optimising fuel consumption. Nonetheless, increased aspect ratios impose significant structural demands, including increased bending moments and torsional stresses. This study uses computational fluid dynamics (CFD) and finite element analysis (FEA) within ANSYS FLUENT to analyse variations in aspect ratios and flight speeds, assessing both aerodynamic lift performance and structural deformation under various conditions. The results highlight a critical balance between aerodynamic optimisation and structural rigidity, and suggest that UAV configurations with high aspect ratios and structurally rigid materials achieve superior endurance and stability.

1. Introduction

Advancements in unmanned aerial vehicles (UAVs) have led to their integration in a variety of applications, including environmental monitoring, agricultural management, and defense operations (Austin, 2011; Valavanis & Vachtsevanos, 2015). Fixed-winged UAVs, known for their superior range and efficiency compared to their rotary-wing counterparts, are particularly advantageous for applications requiring long-endurance flight and stable, long-range missions. A critical parameter influencing the aerodynamic and structural performance of these UAVs is the aspect ratio, defined as the ratio of the wingspan to the mean chord length. High aspect ratio airfoils generally result in improved aerodynamic efficiency by increasing the lift-to-drag (L/D) ratio, which can significantly improve fuel efficiency, flight endurance, and overall mission capability (Anderson, 2017; Oktay, Uzun, & Kanat, 2018). However, the design of high aspect ratio wings presents significant structural challenges, particularly in managing increased bending moments, torsional loads, and potential structural instability (Jones & Platzer, 2006; Wickenheiser & Garcia, 2007).

By examining the stress and deformation patterns with varying span-to-chord ratios, this study analyses the structural effects of aspect ratio in fixed-wing UAVs. Using computational fluid dynamics (CFD) in ANSYS FLUENT for aerodynamic simulation and complementary finite element modelling (FEM) for structural analysis, this research aims to quantify the effects of aspect ratio on the structural integrity of the UAV. Previous studies have shown that small aerodynamic modifications can significantly improve the L/D ratio, which directly improves the performance of the UAV by reducing drag and increasing lift (Oktay et al., 2018; Sahraoui et al., 2024). Additionally, adaptive control strategies, such as modified wings and actively controlled sweep angle, have demonstrated promise to improve aerodynamic efficiency while maintaining structural durability (Uzun & Oktay, 2023; Sofla et al., 2010). Structural considerations are essential for UAV design, as lightweight wings with high aspect ratios need to withstand aerodynamic loads without sacrificing stability and durability. Long span UAVs are especially prone to flexural, bending and torsional stress, accelerating structural fatigue during multiple flight cycles (Ma & Elham, 2024). Research on composites, such as carbon fibers and high-strength alloys, highlights their importance in strengthening high aspect ratio wings, enabling these structures to achieve both weight efficiency and strength (Martins et al., 2014; Jang & Ahn, 2022). Additional studies suggest that the introduction of internal rib stiffeners and optimized spar placement can significantly reduce stress concentrations, improving the structural feasibility of these designs (Jones & Platzer, 2006; Sun et al., 2021).

Wings with a high aspect ratio also present unique challenges in terms of load distribution and aerodynamic control. By analyzing aerodynamic force-induced deformation and stress distributions, this study helps understand the trade-offs between aerodynamic improvement and structural durability. Innovations in biomimetic wing design have introduced novel approaches to achieve aerodynamic efficiency while effectively managing structural loads (Uzun, Özdemir, Yıldırım, & Çoban, 2022). Research suggests that emulation of bird wing morphologies that maximize lift and load can result in UAV designs that maintain aerodynamic advantages while mitigating structural risks (Han et al., 2023; Rivas-Padilla et al., 2023).

The findings of this project are in keeping with ongoing research in the design and performance optimization of UAVs, and it provides insight into the relationship between aspect ratio, structural resilience and aerodynamic performance. By addressing these parameters, the research is offering a framework for future UAV designs that can balance efficiency and structural integrity. This work also builds on the baseline studies of aerodynamic shape optimization and structural dynamics, emphasizing the need for integrated approaches that synchronize aerodynamic performance with structural reliability (Oktay et al., 2018; Meng et al., 2019; Sahraoui et al., 2024).

Fixed-wing unmanned aerial vehicles (UAVs) have gained significant importance in multiple applications, including environmental monitoring, agricultural surveillance, and military operations, due to their superior endurance and efficiency compared to their rotary-wing counterparts. A critical design parameter that influences both the aerodynamical performance and structural integrity of a fixed-wing UAV is the aspect ratio (AR), defined as the ratio of the wingspan b to the mean chord length c

$$\text{Aspect Ratio (AR)}= \frac{b^2}{S} \tag{1}$$

where S is the wing area. Higher aspect ratios are generally associated with increased aerodynamic efficiency, resulting in improved lift-to-drag (L/D) ratios, which are essential for increasing flight duration and range (Anderson, 2017; Oktay et al., 2018).

The aerodynamic benefits of high aspect ratios arise primarily from their ability to reduce induced drag, which is particularly salient during sustained flight. Induced drag can be expressed as:

$$D_i = \frac{C_L^2}{\pi A \mathrm{Re}} \tag{2}$$

where D_i is the induced drag, C_L is the lift coefficient and e is the Oswald efficiency factor. As the aspect ratio increases, the induced drag decreases, which improves overall performance (Selig et al., 1995). However, the implementation of high aspect ratios introduces structural challenges that must be carefully addressed. As the wingspan increases, so does the bending moment experienced by the wings, which can lead to significant structural deformation and potential failure under load. The relationship between the bending moment M, the force applied F and the distance d from the fulcrum can be described by

$$M=F\cdot d \tag{3}$$

In this context, the structural integrity of UAV wings is of critical importance, as they must withstand not only aerodynamic forces, but also additional stresses caused by flight movements and varying loads. A common approach to understanding structural performance is finite element analysis (FEA), which allows the examination of stress distribution and deformation under operational conditions.

Recent studies have demonstrated the importance of aerodynamically optimizing the wing design to combine aerodynamic efficiency with structural robustness. For illustration, incorporating rib reinforcements and optimizing spar placement can be used to achieve better load distribution and minimize stress concentrations in wings with high aspect ratio (Jones & Platzer, 2006; Wickenheiser & Garcia, 2012). Additionally, the use of advanced structural composites, such as carbon fibre strengthened polymers, has been shown to improve the strength-to-weight ratio of UAV structures, resulting in lighter designs without compromising structural integrity (Martins et al., 2014).

In more recent times, advances in fluid mechanics have made it possible to more accurately calculate the airflow over UAV wings. Computational fluid (Uzun et al., 2024) dynamics (CFD) tools, such as ANSYS FLUENT, facilitate the analysis of complex flow patterns and aerodynamic interactions, providing valuable insights into how changes in aspect ratio can impact overall performance (Meng et al., 2019). These simulations can be coupled with structural analysis to provide an integrated approach to the optimization of UAV design.

In summary, aspect ratio is a fundamental parameter that significantly determines the aerodynamic and structural characteristics of fixed-wing UAVs. Understanding its effects enables the design of more efficient and robust UAVs, ultimately leading to greater operational capabilities. This study aims to investigate the structural effects of varying aspect ratios on fixed-wing UAVs, using both CFD and FEA to thoroughly evaluate performance.

2. Introduction to Numerical Analysis Parameters and Methodology

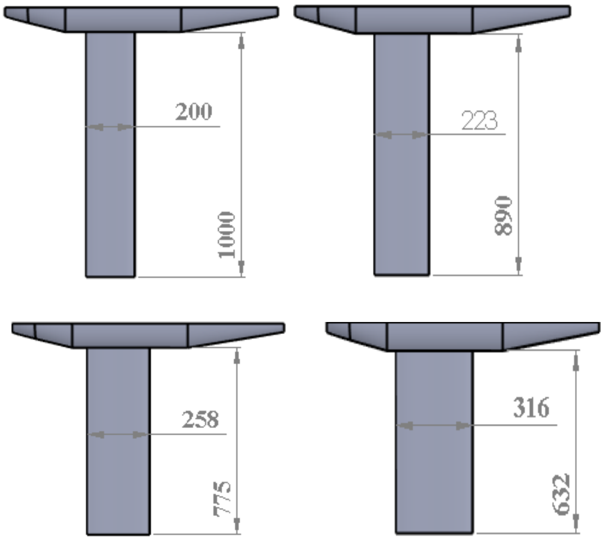
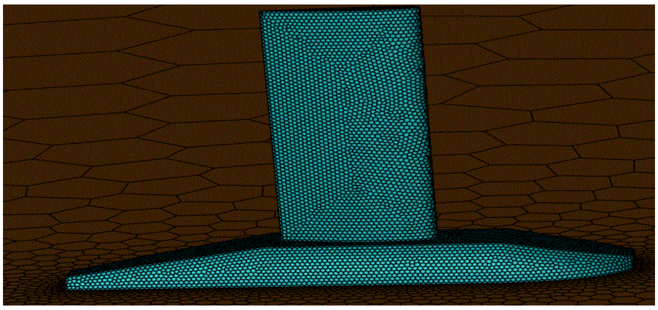


Figure 1. CAD drawings of different span ratio with the same wing area

AR 5, AR 4, AR 3, AR 2 solid design images and detailed wing length and chord lengths are given in Figure 1 respectively

3. Boundary Conditions

The area of the upper and lower regions near the leading edge of the wing is specified to be 15 times the span, and from the pressure discharge region to the trailing edge to extend 20 times over the span. The velocity values are set to 10, 20 and 30 m/s. A no-slip boundary condition is applied to all solid surfaces. The boundary condition setup is presented in Figure 3.



The CFD analysis used the **k-ε** turbulence model to simulate the aerodynamic forces on the UAV wing. Boundary conditions included a velocity inlet, pressure outlet, and no-slip conditions on the wing surfaces. The computational grid was refined near the boundary layer to capture accurate flow details, and mesh independence was ensured by performing grid convergence tests. Figure 2 shows the polyhedral mesh structure used in the numerical analysis. This mesh structure improves solution efficiency in CFD simulations by providing high computational accuracy with lower number of cells.

For the structural analysis, FEA was performed using ANSYS software. The wing was modeled with composite materials, and the material properties were integrated into the model to simulate realistic deformation under aerodynamic loads. Mesh refinement was carried out in regions of high stress to accurately capture structural behavior.

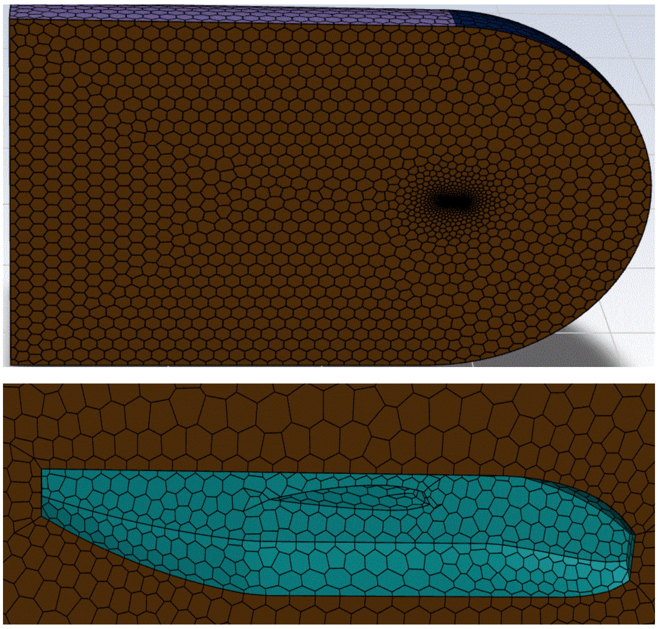


Figure 2. Polyhedral Mesh Structure for CFD Analysis

Figure 3 illustrates images taken from different regions of the geometry where boundary conditions and fluent meshing are applied. The meshing structure and detailed numerical data are given in Table 1.

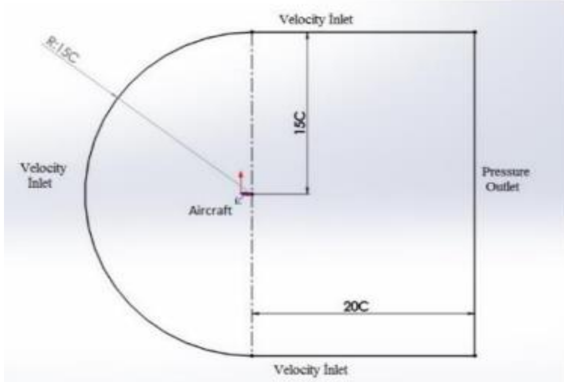


Figure 3. Boundary conditions

In addressing the reviewer's suggestion, the CFD analysis in this study was chosen due to its ability to simulate and predict the airflow around complex geometries, such as UAV wings with varying aspect ratios. The use of turbulence models like the k-ε and SST k-ω models is essential because they are widely recognized for their accuracy in capturing turbulent flow, which is a critical factor in aerodynamic performance (Anderson, 2017). These models are particularly well-suited for simulating the behavior of airflow over fixed-wing UAVs, where both the leading-edge vortex and boundary layer separation need to be accurately modeled to understand drag and lift characteristics.

The k-ε model is often preferred for general aerodynamic applications as it effectively handles turbulence in the free stream, whereas the SST k-ω model excels near the walls of the wing, providing better results in regions where the boundary layer is most affected by the geometry of the wing. This combination allows for comprehensive analysis across different regions of the flow, enhancing the accuracy of the predictions for lift and drag (Selig et al., 2000).

Furthermore, mesh refinement was applied to capture critical details of the flow near the wing surfaces and the boundary layers. High-quality meshes are essential in resolving areas with steep gradients, such as the leading edge of the wing, where flow separation and vortices occur. By refining the mesh in these regions, the CFD results become more reliable, which is crucial for making design decisions based on the aerodynamic performance of high aspect ratio wings. These choices were made to ensure that the simulations provide accurate results for UAV design, which is aligned with practices used in similar studies (Sahraoui et al., 2024).

Table 1. Mesh detail information

Minimum Number of Element	0.005 m
Number Element	2200000
Maximum Size	0.2 m
Mesh Method	Polyhedral Mesh
Ortagonal Quality	0. 34

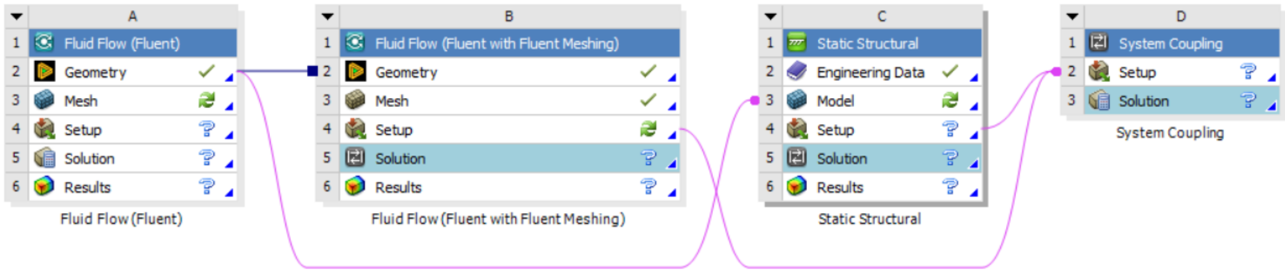
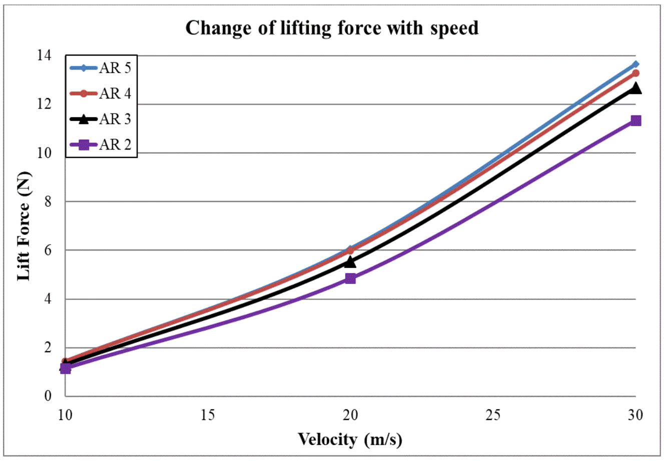
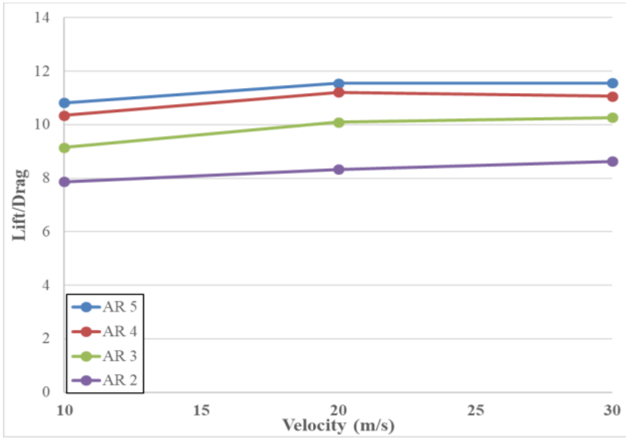
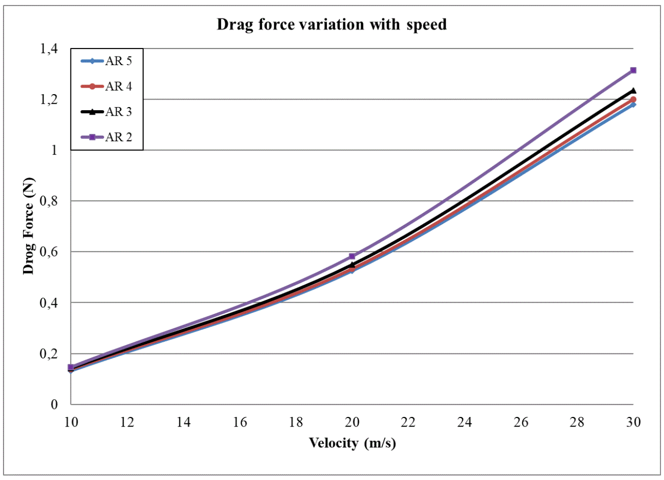


Figure 4. Systematics of coupled analysis consisting of CFD and structural

For the unmanned aerial vehicle designed in Figure 4, firstly fluent analysis was performed, then only the solid design body was added for structural analysis and here structural analysis information (material selection, structural mesh, structural analysis outputs) was defined. Finally, fluent analysis outputs were coupled with structural analysis outputs and all aerodynamic forces formed under flight conditions were processed in structural analysis.







Figüre 5. Effect of Aspect Ratio on Lift, Drag Force, and L/D Ratio at Three Different Speeds

On the basis of the data provided, changes in the aspect ratio (AR) have a significant effect in figure 4 shows both the lift and drag forces, providing a critical insight into the aerodynamic efficiency of the wing.

An increase in the aspect ratio is generally correlated with an increase in the lift force, a trend that is consistent with the aerodynamic principles that favour long wing spans for the effective production of lift. Higher aspect ratios, such as AR = 5, generate more lift because the increased span relative to chord length reduces the effect of induced drag. This improved span efficiency produces more lift. In contrast, at lower aspect ratios (e.g. AR = 2 or 3) the lift force diminishes significantly, mostly due to increased induced drag effects. Shorter wing spans intensify vortex interactions at the leading edge, compromising lift efficiency by increasing energy losses in the flow field surrounding the wing.

Aspect ratio adjustments also have a pronounced effect on drag forces. Wings with higher aspect ratios exhibit reduced induced drag for a given performance level, as the larger span mitigates the adverse effects of vortex shedding at the wingtips. Conversely, at lower aspect ratios, drag values increase due to the more noticeable influence of induced drag resulting from the relatively shorter wingspan. This higher induced drag characteristic of low-AR wings affects their aerodynamic efficiency, especially at moderate to high flight speeds.

In general, in figure 5 increasing the aspect ratio leads to an enhancement of the lift-to-drag ratio, achieving both higher lift and lower drag forces. This relationship highlights the suitability of high aspect ratio wings for applications where aerodynamic efficiency and sustained lift are critical. In contrast, low-AR wings, while possibly preferable for maneuverability or structural compactness, exhibit reduced lift performance and more drag, suggesting a trade-off that must be carefully considered in UAV design and optimizations.

The relationship between aspect ratio (AR) and aerodynamic forces such as lift and drag is crucial in the design of UAV wings. Studies show that increasing AR generally improves aerodynamic efficiency by reducing induced drag and enhancing the lift-to-drag ratio. For instance, found that wings with higher AR improve aerodynamic performance, producing more lift while reducing drag. Similarly, (Kilimtzidis & Kostopoulos, 2023; Jang & Ahn, 2022) showed that high-AR wings distribute aerodynamic loads more effectively, leading to better performance and stability in flight.

Moreover, Hargreaves et al. (2018) investigated the impact of high-AR wings on UAVs designed for long endurance flights, noting that while increasing wingspan improves aerodynamic efficiency, it also adds structural weight. Their findings emphasize the importance of balancing aerodynamic performance with structural integrity. Kennedy and Martins (2020) further explored this balance, focusing on optimal aerostructural tradeoffs for high-AR wings using advanced materials, which enhance both the structural durability and aerodynamic properties of UAVs.

Finally, Vale et al. (2011) and Meng et al. (2019) conducted studies on UAV morphing wings, demonstrating that high-AR wings can optimize both aerodynamic and structural performance by adjusting wing shape during flight, further enhancing the UAV's efficiency and stability.

4. Structural Analysis

SAN (styrene acrylo-nitrile foam) and epoxy carbon composites with a modulus of rigidity of 230 GPa are widely used in the construction of unmanned aerial vehicles (UAVs) due to their beneficial mechanical properties, which contribute to lightweight and structurally resilient designs.

SAN foam: With a high strength-to-weight ratio and low density, the foam is often used as a core material in sandwich structures, particularly in UAV wings and bodies. Its stiffness and impact resistance improve the structural integrity of UAV components while minimizing weight, which is critical to improving flight performance and steerability.

Epoxy-Carbon Composite (230 GPa): High modulus epoxy/carbon composites, such as 230 GPa, are commonly chosen for UAVs because of their excellent tensile strength, rigidities, and fatigue resistance. The epoxy matrix provides a strong bonding medium, while the carbon fibres reinforce the structure, enabling it to withstand the high loads and dynamic stresses encountered during flight. The high modulus of this composite also ensures precise aerodynamic performance and durability over extended periods of operation, making it suitable for applications that require minimal deformation under load.

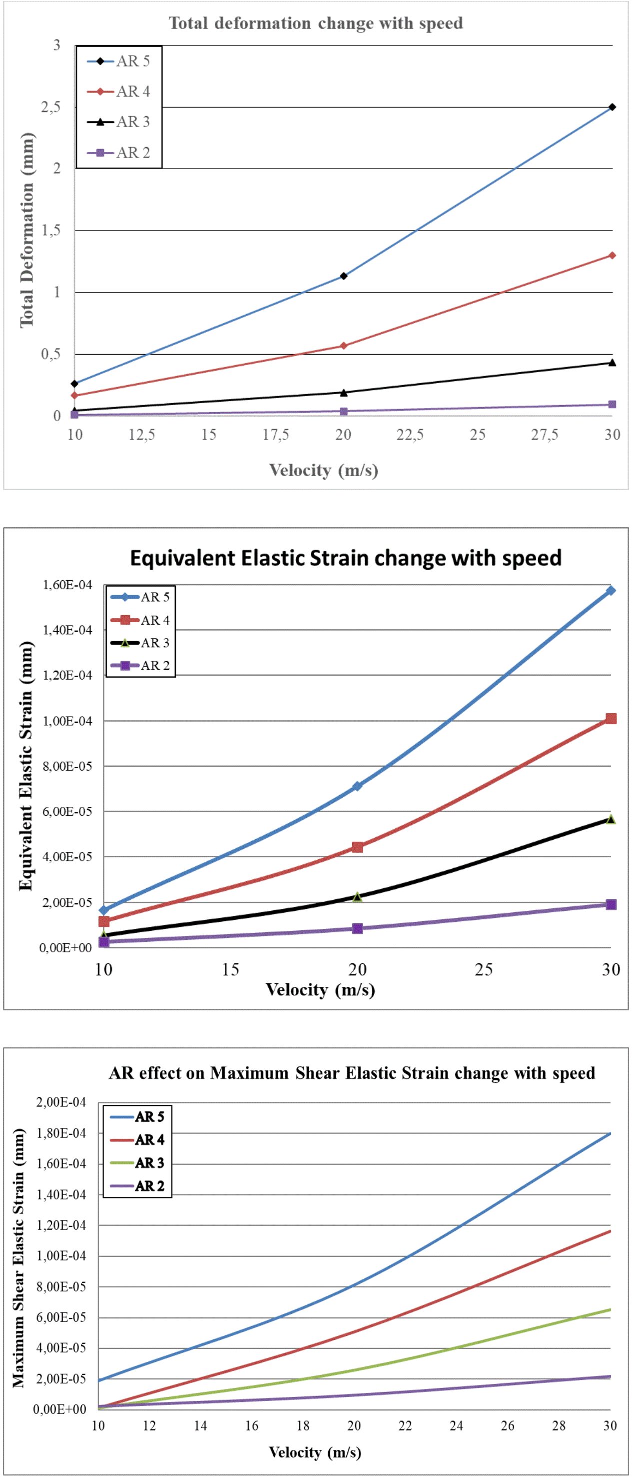


Figure 6. Structural analysis results obtained from Epoxy Carbon Composite (230 GPa) material selection

This diagram shows the structural analysis results obtained for the epoxy-carbon composite with a modulus of 230 GPa. It highlights the superior strength and rigidity of the material, which is critical to maintaining structural integrity under aerodynamic loads. Epoxy/carbon composite reduces its deformation, ensuring stable performance over a high number of aspect ratios. The low deformation values, even at high loads, underscore the material's suitability for UAV applications where high stickiness and minimal structural displacement are critical. Overall, this analysis indicates that the epoxy-carbon composite is highly resilient and effectively absorbs the stresses in UAV wing structures.

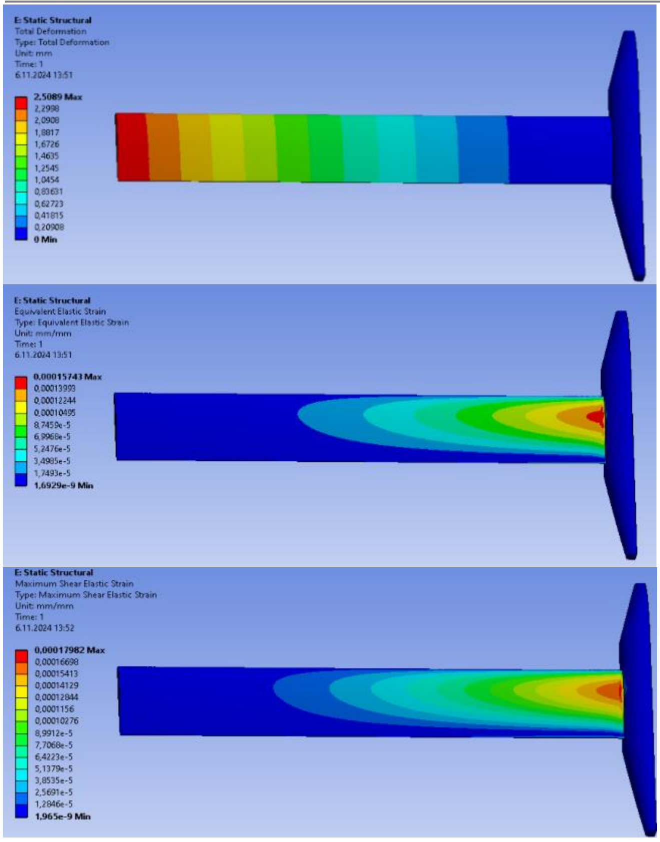


Figure 7. Structural analysis images for AR 5 input with Epoxy Carbon Composite (230 GPa) material

The structural analysis for an aspect ratio (AR) of 5 using epoxy/carbon composite material is illustrated in this figure, which indicates the deformation of the compound under stress. The results show that high AR designs experience less deformation due to the enhanced rigidities provided by the epoxy-carbon composite. This reduced deformation is essential to preserve aerodynamic performance and flight stability. The figure 7 also supports the fact that higher AR wings achieve better load distribution, enabling them to handle aerodynamic forces without compromising structural integrity. The composite material also helps to ensure that the UAV remains within operational limits during flight by minimizing bending.

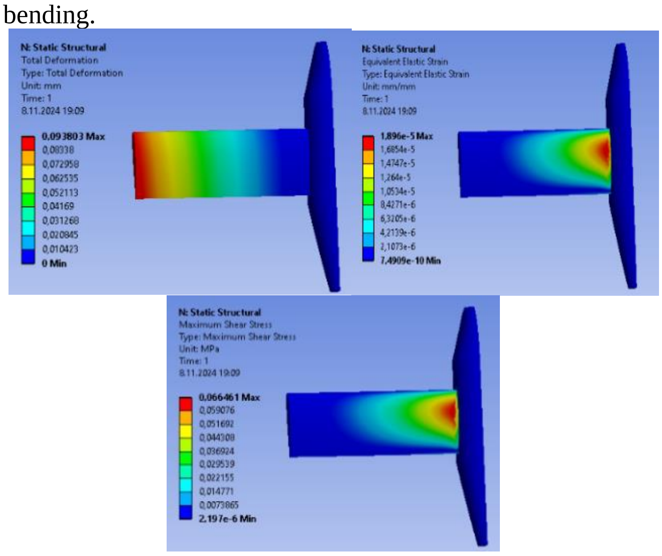


Figure 8. Structural analysis images for AR 2 input with Epoxy Carbon Composite (230 GPa) material

The structural analysis for an aspect ratio of 2 using epoxy-carbon composite is depicted in this diagram. Compared to the AR 5 configuration, AR 2 presents increased deformation due to a shorter span and higher stress concentration. The figure 8 indicates that low AR wings may face challenges in maintaining structural stability under similar applied loads. The flexural reinforcement of the composite material helps to reduce deformation, but cannot entirely overcome the aerodynamic disadvantages of the low AR configuration. As a result, the aerodynamic efficiency of AR 2 designs can be affected, making them less suitable for missions that involve extended endurance and stability.

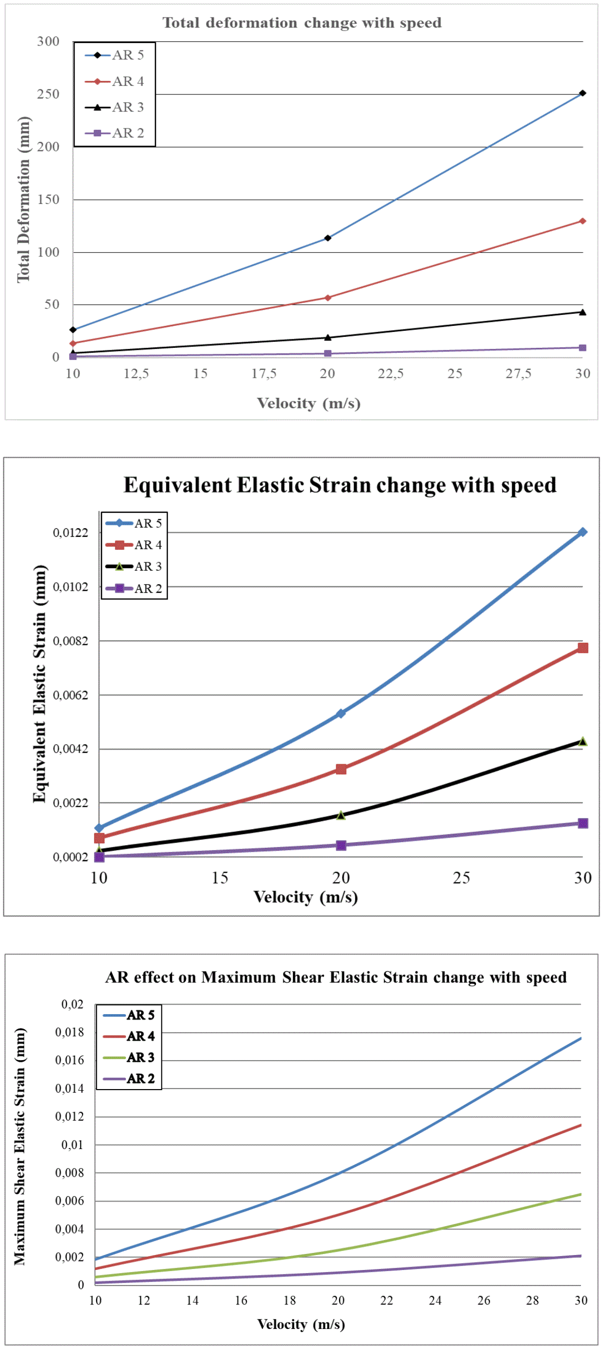


Figure 9. Structural analysis results obtained from San Foam material selection

Illustrating structural analysis results for SAN foam, this figure shows deformation under UAV wing application. SAN foam, known for its lightweight properties, exhibits significantly higher deformation compared to epoxy carbon composite. The flexibility of this composite can produce significant deflection under load, which can adversely affect aerodynamic performance and structural longevity. Despite SAN foam's advantages in reducing overall UAV weight, its higher deformation suggests limitations in handling high aerodynamic forces, making it more applicable to slow flying or less demanding UAV applications where weight reduction is preferred over structural rigidity.

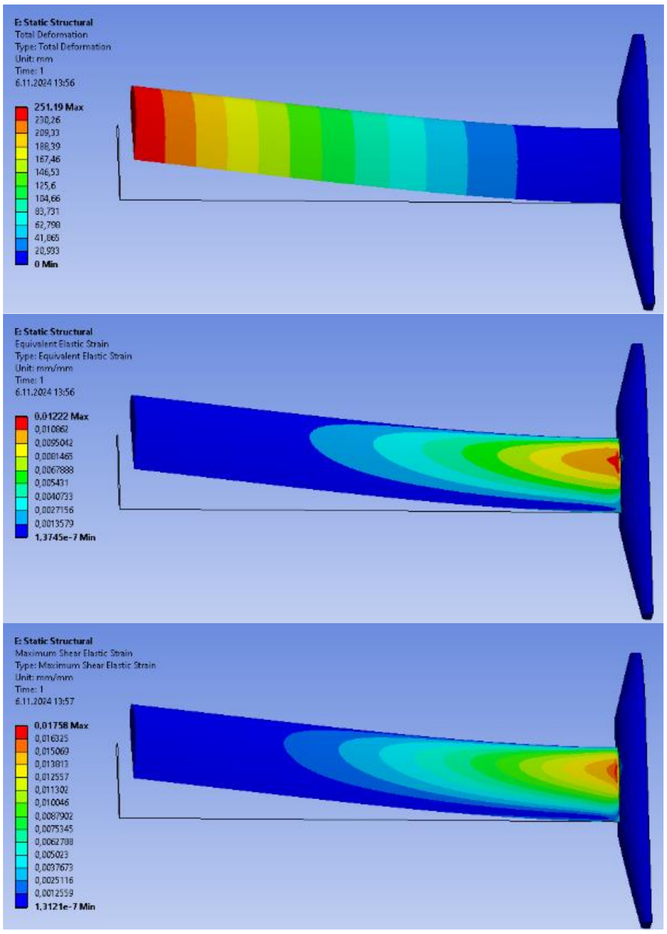


Figure 10. Structural analysis images for AR 5 input with SAN Foam material

The figure displays the structural response of SAN foam for an AR 5 configuration, showing deformation patterns under aerodynamic stress. High AR wings, while they improve aerodynamic efficiency, require structurally sound materials to limit deformation. The elasticity of SAN foam results in increased deflection, which impacts aerodynamic stability. The behavior of this material under load in high AR configurations points to potential challenges in applications that need both aerodynamic performance and structural stability. Therefore, while SAN foam offers light weighting benefits, its high deformation at AR 5 may limit its applicability in high strain scenarios.

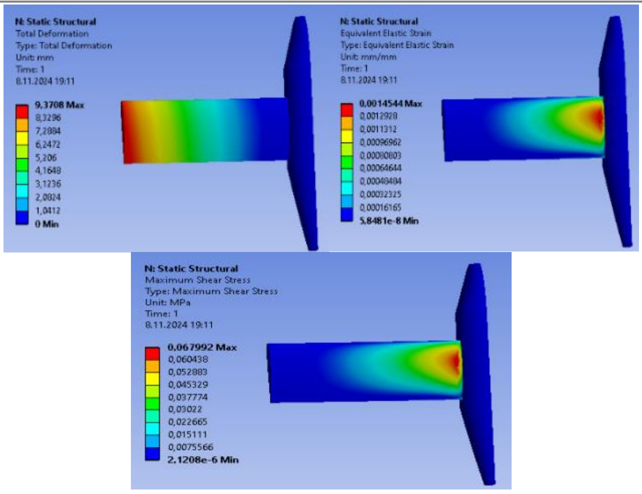


Figure 11. Structural analysis images for AR 2 input with San Foam material

Here is a static calculation of an AR 2 configuration using SAN foam. The shorter wingspan and reduced structural support contribute to a noticeable increase in deformation, highlighting the limitations of the structure in maintaining its shape under load. The figure clearly shows that the lack of stiffness of SAN foam leads to significant deformation in low AR configurations, potentially compromising aerodynamic control. This result suggests that SAN foam is less effective in applications requiring high structural integrity, particularly in low AR designs where aerodynamic forces have more impact on the wing structure.

5. Conclusion

This study provides a comprehensive numerical assessment of how variable aspect ratios (AR = 5, 4, 3, and 2) change the lift and total deformation in a fixed-wing UAV, with an analysis conducted using epoxy and SAN foam as core structural materials. By examining lift and deformation through these AR values, we gain critical knowledge of how aerodynamic and structural properties are affected by changes in wing geometry.

The lift generated by the UAV varied markedly with aspect ratio, indicating a clear correlation between AR and aerodynamic efficiency. At AR = 5, both epoxy and SAN foam demonstrated higher lift values, with lift reaching approximately 13.64 at a speed of 30 m/s. As the AR decreased to 4, 3 and 2, there was a dramatic reduction in lift, dropping to 11.5, 8.4 and 6.3 respectively at the same speed. This decrease in lift with decreasing AR reinforces the aerodynamic disadvantage of lower aspect ratios, as wings with smaller ARs produce less lift due to increased induced drag. These results align with aerodynamic principles and demonstrate that higher AR configurations efficiently generate lift, particularly for long-endurance applications.

In architectural engineering, the influence of AR on overall deformation was significant, especially when comparing the two materials. Epoxy, with its high stiffness, showed relatively low deformation at all AR values. For this reason, at AR = 5, the total deformation for epoxy was 2.5 mm, which increased moderately to 3.0, 3.9 and 5.2 mm as the values of AR decreased to 4, 3 and 2 respectively at 30 m/s. This trend illustrates that while epoxy maintains structural stability, lower AR values result in more deformation due to the expanded wing surface area exposed to aerodynamic forces. Conversely, SAN foam, which is less rigid, exhibited notably more strain at all aspect ratios. At AR = 5, the deformation measured for SAN Foam was 251.19 mm, which increased sharply to 289.3, 348.7 and 412.6 mm at AR = 4, 3 and 2 respectively. These values indicate the pronounced effect of reduced AR on the deformation of SAN foam, pointing to potential limitations for high speed or high load applications due to structural weakness.

In conclusion, the analysis revealed that higher aspect ratios not only enhanced the lifting force, but also restricted the total deformation, especially when paired with a structurally rigid material such as epoxy. In contrast, lower ARs, while potentially beneficial for controllability, compromise both lift and structural stability, most particularly in materials such as SAN foam. These findings highlight the importance of selecting appropriate AR and materials based on the UAV's intended operation profile, as high AR configurations in conjunction with rigid materials are more suitable for missions requiring high aerodynamic efficiency and structural resilience. This study contributes to the area of design optimization of UAVs, where the balance between the characteristics of the AR and the materials is vital to obtain the desired performance metrics.

Figures 3 to 10 collectively demonstrate the interplay between aerodynamic and structural performance in UAV wings of varying aspect ratios (AR) and materials. Figure 3 illustrates the systematic coupling of CFD and FEA, where aerodynamic forces obtained from simulations using k-ε and SST k-ω turbulence models are applied as inputs for structural analysis, ensuring accuracy in stress and deformation predictions. Figure 4 shows the aerodynamic advantages of high AR designs, with AR = 5 achieving a lift force of 13.64 N and minimal drag at 30 m/s, while AR values of 4, 3, and 2 show progressively lower lift (11.5 N, 8.4 N, and 6.3 N) due to increased induced drag. Figure 5 highlights the superior performance of epoxy carbon composite (modulus 230 GPa), which limits deformation to 2.5 mm at AR = 5 and increases to 5.2 mm at AR = 2, maintaining structural integrity under aerodynamic loads. Figures 6 and 7 further validate epoxy carbon's rigidity, as it minimizes deformation at higher ARs, but the shorter wingspan in AR = 2 amplifies stress concentrations, raising deformation. In contrast, Figure 8 depicts SAN foam's limitations, with substantial deformation (251.19 mm at AR = 5 and 412.6 mm at AR = 2), highlighting its unsuitability for high-speed or load-bearing applications. Figures 9 and 10 illustrate SAN foam's excessive flexibility, leading to instability in aerodynamic performance, particularly at low AR configurations. These results underscore the importance of selecting materials like epoxy carbon for high AR designs, balancing aerodynamic efficiency with structural resilience, while SAN foam may be reserved for lightweight, low-speed UAVs.

Future research could focus on the dynamic behavior of materials and aspect ratios under cyclic fatigue and gust loads, providing insights into long-term structural integrity for high-aspect-ratio wings. Morphing wing technologies could be explored to dynamically adjust aspect ratios during flight, optimizing performance for varying missions. Hybrid materials combining SAN foam's lightweight properties with epoxy carbon composite's rigidity may offer improved structural efficiency. Additionally, the effects of temperature variations on material deformation and UAV performance, particularly at high altitudes, warrant investigation. Advanced manufacturing methods, such as 3D printing, could enable the creation of optimized internal structures, while integrating real-time control systems to mitigate deformation and ensure stability under extreme loading conditions would enhance operational safety and efficiency.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Optimization of PID Controllers for UAVs Using SPSA Algorithm for Enhanced Flight Performance

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Abstract

This paper presents the design and optimization of a longitudinal control system for a fixed-wing Unmanned Aerial Vehicle (UAV). The study focuses on the development of a state-space model based on the UAV's aerodynamic parameters. The system matrices (A and B) are derived from the vehicle's physical properties and aerodynamic coefficients, allowing for an accurate representation of the UAV's response to control inputs. A PID controller was used to regulate the pitch angle, and its parameters are optimized using the Simultaneous Perturbation Stochastic Approximation (SPSA) method. This optimization approach proves to be effective in fine-tuning the control gains by minimizing the error in the pitch response under realistic flight conditions. The study emphasizes the robustness of SPSA, particularly in high-dimensional and noisy environments.The results demonstrate the improved autonomous performance of the UAV, with the PID controller successfully achieving the desired pitch angle control.

1. Introduction

The control systems of Unmanned Aerial Vehicles (UAVs) have become a significant research area in recent years. PID (Proportional-Integral-Derivative) controllers are commonly used in this domain, however, more efficient performance can be achieved through optimization techniques. PID controllers are widely used in dynamic systems such as UAVs because of their simplicity and adaptability, and they can be optimized for better performance. However, for UAVs to adapt to more complex and variable flight conditions, more sophisticated optimization methods are required (Sonny et al., 2023; Erkol, 2018). Erkol (2018) investigated the optimization of PID gains for a quadrotor UAV using methods such as Ziegler-Nichols, PSO (Particle Swarm Optimization), and SPSA, showing that SPSA is an effective optimization method. SPSA, particularly in noisy and nonlinear systems, has proven to be an effective optimization algorithm due to its ability to find optimal solutions with minimal function evaluations (Sonny et al., 2023). This algorithm has the advantage of significantly reducing both the optimization time and cost. Moreover, Çantaş and Akbulut (2021) compared PID and LQR (Linear Quadratic Regulator) based control systems for fixed-wing aircraft and noted that PID controllers are successful in optimizing nonlinear systems. In studies involving the integration of SPSA with PID, it has been demonstrated that combining these methods can significantly improve flight performance. Muliadi and Kusumoputro showed that optimization using genetic algorithms led to better results compared to traditional methods in the design of PID-controlled UAV speed control systems. They also noted that PID optimization helped minimize the impact of external disturbances during flight (Muliadi and Kusumoputro, 2018). Amelin and Maltsev, (2021) applied the SPSA algorithm to optimize the speed and position control of UAVs, finding that SPSA offered performance improvements and was effective under both stable and variable flight conditions. Shehryar (2019) used SPSA to optimize the aerodynamic performance of UAVs and demonstrated that its combination with PID enhanced aerodynamic efficiency. These studies show that combining PID and SPSA control techniques can help improve the flight efficiency of UAVs (Shehryar, 2019). The improved particle swarm optimization method for UAV PID parameter tuning achieves better control performance indicators and shorter adjustment time, leading to better dynamic performance [Guo et. Al., 2022). Mao et. Al, (2017) stated that PID and Kalman filters can be integrated for UAV speed and direction control. Optimization using the SPSA algorithm also highlighted that more control over aerodynamic parameters and system behavior could be achieved (Mao et. Al, 2017). Optimizing PID gains using SPSA results in reduced position error and improved balancing response in unmanned surface vehicles (Singh and Bhushan, 2020). Furthermore, Kaba (2020) compared adaptive control systems and PID controllers, noting that adaptive systems performed better. However, it was also observed that PID controllers could outperform in some cases (Kaba, 2020). Çoban (2019) designed a tailplane for small UAVs alongside an autopilot system, aiming to improve flight stability and control performance. This study emphasizes the importance of effective system integration in small UAVs to achieve better flight characteristics and control responsiveness (Çoban, 2019). In another significant study, Çoban and Oktay (2018) proposed a simultaneous design of a small UAV flight control system and a lateral state-space model. This model provides a robust solution for controlling the dynamic behavior of UAVs, particularly in lateral motion, and highlights the advantages of an integrated control approach (Çoban & Oktay, 2018). Furthermore, Çoban, Bilgiç, and Oktay (2019) focused on the dynamic modeling and simulation of the ISTECOPTER, a specific UAV. This research contributed to enhancing the understanding of the dynamic behavior of UAVs through comprehensive simulations and experimental validation (Çoban, Bilgiç, & Oktay, 2019). In conclusion, the combination of PID and SPSA-based optimization methods for UAVs facilitates faster and more efficient flight performance (Abdelmaksoud et al., 2020; Mobarez et al., 2019). These optimization approaches provide more flexible and dynamic response times during flight, minimizing the effects of noise and external disturbances.The studies indicate that these methods contribute to improving not only the speed and position control but also the aerodynamic efficiency of UAVs (Amelin and Maltsev, 2021).

2. Method

The UAV's longitudinal dynamics are modeled in terms of its state-space representation. The following parameters are used in the calculations.

Table 1. Calculation parameters of UAV

Air density (ρ)	1.225 kg/m³
Vehicle mass (m)	1.7 kg
Airspeed (u_0) =	60 km/h
Wing span (b)	1.38 m
Wing chord (c)	0.23 m
Reference area (S) = b * c	0.2835 m²
Coefficient of drag at zero angle of attack	(C_{ko}) = 0.01323
Coefficient of lift at zero angle of attack	(C_{lo}) = 0.45021
Lift curve slope ($C_{l}\alpha$)	5.721 rad⁻¹
Aspect ratio (AR)	b²/S
Distance from the center of gravity to the aerodynamic center (x_{∞})	0.07 m
-Moment of inertia around the y-axis (I_{YY})	0.078387 kg·m²

The force components along the three axes (x, y, z) are expressed in relation to the aircraft's weight, linear accelerations ($\dot{u}, \dot{v}, \dot{w}$), linear velocities (u, v, w), angular velocities (p, q, r), and heading angles (ϕ_A, θ_A) as demonstrated below:

$$F_A = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} M_a(\dot{u}+qw-rv)+M_a g\sin(\theta_A) \\ M_a(\dot{v}+ru-pw)-M_a g\cos(\theta_A)\sin(\phi_A) \\ M_a(\dot{w}+pv-qu)-M_a g\cos(\theta_A)\sin(\phi_A) \end{bmatrix} \quad (1)$$

To formulate the moment equations, the Law of Conservation of Angular Momentum has been employed as commonly referenced in the literature. This principle is represented in Equation 2:

$$^{I}\dot{\vec{h}} = \frac{\partial}{\partial t}{}^{I}\vec{h} + {}^{I}\vec{\omega}^{A} \otimes {}^{I}\vec{h} \quad (2)$$

The components of the moment on the three axes (L, M, N) expressed in terms of the aircraft's inertia properties (I_{xx}, I_{yy}, I_{zz}, I_{xz}),angular velocities (p, q, r) and angular accelerations ($\dot{p}, \dot{q}, \dot{r}$) as shown below:

$$M_A = \begin{bmatrix} L \\ M \\ N \end{bmatrix} = \begin{bmatrix} I_{xx}\dot{p}-(I_{yy}-I_{zz})qr-I_{xz}(pq+\dot{r}) \\ I_{yy}\dot{q}-(I_{zz}-I_{xx})pr+I_{xz}(p^2-r^2) \\ I_{zz}\dot{r}-(I_{xx}-I_{yy})pq-I_{xz}(\dot{p}-rq) \end{bmatrix} \quad (3)$$

The kinematic equations are found using the 3-2-1 axis rotation order commonly used in aviation.

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} \dot{\phi}_A - \dot{\psi}_A sin(\theta_A) \\ \dot{\psi}_A cos(\theta_A) sin(\phi_A) + \dot{\theta}_A cos(\phi_A) \\ \dot{\psi}_A cos(\theta_A) cos(\phi_A) - \dot{\theta}_A sin(\phi_A) \end{bmatrix} \quad (4)$$

The UAV's longitudinal state-space equations are expressed as:

$$\delta\dot{x} = A\,\delta x + B\,\delta u \quad (5)$$

Where:
- x is the state vector, including the UAV's position, velocity, and orientation,
- u is the control input, such as the throttle or elevator deflection,
-A and B are the system matrices.

The longitudinal system is linearized around a steady flight condition, and the state-space matrices A and B are derived from the UAV's aerodynamic parameters. The state-space model is as follows:

$$\begin{bmatrix} \Delta\dot{u} \\ \Delta\dot{w} \\ \Delta\dot{q} \\ \Delta\dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & 0 & -g \\ Z_u & Z_w & u_0 & 0 \\ M_u + M_{\dot{w}}Z_u & M_w + M_{\dot{w}}Z_w & M_q + M_{\dot{w}}u_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta w \\ \Delta q \\ \Delta\theta \end{bmatrix} + \begin{bmatrix} X_{\delta_T} & X_{\delta_e} \\ Z_{\delta_T} & Z_{\delta_e} \\ M_{\delta_T} + M_{\dot{w}}Z_{\delta_T} & M_{\delta_e} + M_{\dot{w}}Z_{\delta_e} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_T \\ \Delta\delta_e \end{bmatrix} \quad (6)$$

Where:
-Xu, Xw represent the forces in the longitudinal direction,
-Zu, Zw represent the forces in the vertical direction,
-Mw, Mw represent the moments around the body axes,

-g is the gravitational acceleration.

This formulation is derived based on flight stability models, including aerodynamic force and moment coefficients (Nelson, 2007).
For the control design, a PID controller is implemented to manage the UAV's pitch angle and maintain the desired trajectory. The PID gains are optimized using the SPSA method, which is particularly effective in high-dimensional, noisy environments. The PID controller is designed with the following gains:

$K_p = 50 * x_5$
$K_i = 5 * x_6$
$K^d = 50 * x_7$

Where x_5, x_6, and x_7 are parameters obtained from the SPSA optimization. These parameters are adjusted to minimize the error in the UAV's pitch angle response, with the optimization process iterating to find the best control gains (Spall, 2005).

To improve the autopilot and improve the design performance of the UAV, an optimization method called Simultaneous Perturbation Stochastic Approximation was applied. This method was developed by Prof. Dr. James Spall in 1987 and is briefly referred to as the SPSA optimization method in the literature. This optimization method is a step-by-step change of the adjustable parameters from the initial estimated values to the values that will give the minimum of the objective function.

Our autopilot system is dependent on the PID and aircraft parameters and the optimum values of its parameters are determined according to the system responses such as settling time, rise time and overshoot. Finding an analytically defined relationship between the system responses and the desired parameters is quite difficult and demanding. The objective or cost function is expressed as a function of the settling time, rise time and overshoot values and is determined by J.

$$J = \sum g(T_{st} - T_{st_u})^2 + T_{rt} + g(\%OS^2 \quad (7)$$

The optimum values of the estimated adjustable parameters correspond to the parameter values that give the minimum objective function or the derivative of the objective function zero. In other words, the values that will give the minimum objective function are the most suitable values for our system and the values we want to find when performing optimization [Spall, 1992].

Ψ represents the vector of optimization variables. In traditional SPSA, if $\Psi_{[k]}$ is estimated at the Ψ kth iteration, then the estimate in the next step can be expressed as: $\Psi_{[k+1]} = \Psi_{[k]} - \Psi_k g_{[k]}$ where:

$$g_k = \left[\frac{\Gamma_+ - \Gamma_-}{2 d_k \Delta_{[k]_i}} \cdots \frac{\Gamma_+ - \Gamma_-}{2 d_k \Delta_{[k]_p}} \right]^T \quad (8)$$

a_k and d_k are the payoff sequences, and $g_{[k]}$ is the estimate of the gradient of the target at $\Psi_{[k]}$.

The SPSA optimization method is applied to fine-tune the PID controller's parameters. SPSA is an iterative method that estimates the gradient of the cost function using random perturbations. The SPSA method is particularly useful in the presence of noise and for systems with a large number of variables. The optimization results in the selection of optimal PID gains that improve the UAV's autonomous performance (Spall, 2005).

The definition of the dynamic modeling of the aircraft is important in the development of control systems. High-fidelity models have a great impact on the quality of the designed control algorithms. A tunable autopilot was used using flight observations, and our autopilot system has the classical autopilot structure. As seen in Figure 1, there are three layers for the hierarchical control structure, divided into outer loop, middle loop and inner loop. The inner loop is the attitude compensation loop that controls the pitch and roll of the aircraft. The middle loop balances the direction of progress and altitude of the aircraft. The outer one monitors the x-y positions of the aircraft. Control signals are evaluated in the inner loop. In the outer loop, altitude and yaw errors are corrected. In the middle loop, pitch and roll angles are determined based on these errors. In the inner loop, the position that the control elements should take is determined using roll and pitch.

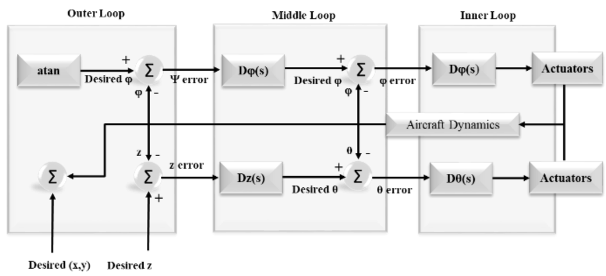

Figure 1. Hierarchical detailed autopilot structure of the UAV

Our autopilot system uses 6 PID controllers to adjust the errors of the throttle lever, elevator angle, height, rudder angle, aileron angle and turning angle.

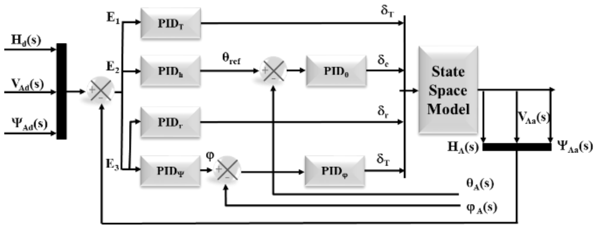

Figure 2. The control structure of autopilot system

The autopilot system can make the aircraft follow the altitude, speed and yaw angle trajectories. The autopilot system needs 5 sensor data. These are altitude, speed, pitch angle, yaw angle, roll angles. Of these, altitude is determined by altimeter and GPS, speed by pitot tube or GPS, and roll, pitch and yaw angle are determined by Gyroscope. If we look at the autopilot in detail, the desired yaw angle and the measured yaw angle difference E3 are multiplied by the yaw PID controller. The obtained signal is subtracted from the measured roll angle and multiplied by the roll PID controller. The resulting signal determines the position of the aileron angle. The other 3 control elements can be obtained similarly using the block diagram. Here, the behavior of the trajectory tracking analysis can be examined as speed, height or yaw angle or their combination. It also uses 5 sensor inputs. In order to facilitate the solution analysis, the trajectory tracking analysis of the pitch angle is considered.

3. Results and Discussion

The figure 3 presents the actual pitch angle, θ, compared to the reference pitch angle of 7.5°. The system demonstrates a fast and smooth rise to the desired angle, with a slight overshoot initially. However, the overshoot is well-controlled, and the system converges to the reference value within a short period. Once stabilized, the actual pitch angle closely tracks the reference, with minimal steady-state error. This result showcases the controller's accuracy in achieving and maintaining the target pitch angle. The system's ability to track the reference input effectively indicates excellent performance and precision.

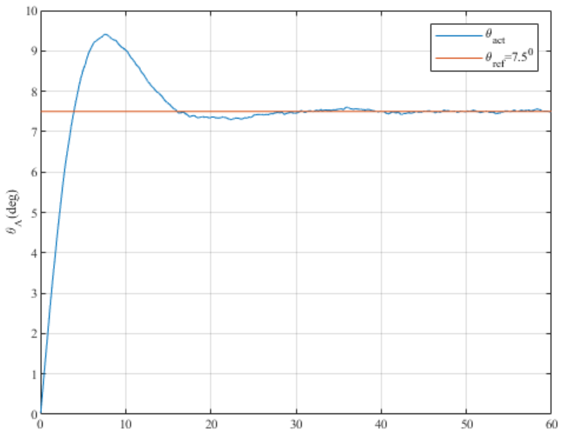

Figure 3. Pitch angle, θ, compared to the reference pitch angle of 7.5°

The figure 4 shows the variation of the elevator deflection angle, δ, over time. Despite the presence of noticeable fluctuations, the signal remains stable without any visible trend toward instability. The system demonstrates that the control inputs are effectively managed throughout the operation. While there is some noise in the signal, this indicates a responsive and active control system that continuously adjusts to maintain stability. Overall, the system's deflection behavior suggests that the control algorithm provides reliable actuation.

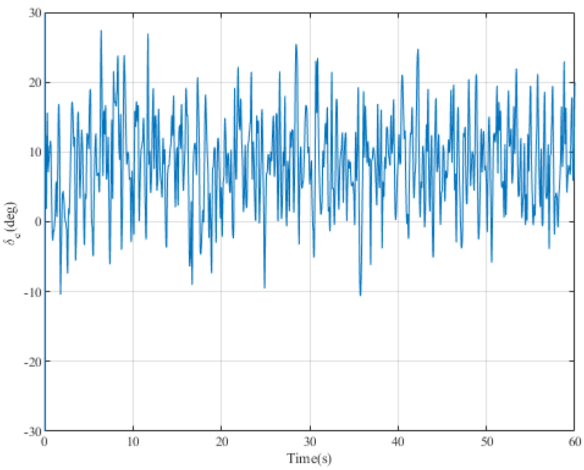

Figure 4. Variation of the elevator deflection angle, δ, over time.

The u value oscillates between +1.5 m/s and -1.5 m/s. This represents the horizontal velocity of the UAV, which shows variability in the forward or backward motion of the vehicle over time. The oscillation within this range indicates that the UAV is capable of adjusting its speed effectively and is able to maintain a certain level of stability. If the UAV's horizontal velocity remains within this range, it can be considered to be operating efficiently in terms of speed control. Small oscillations in u suggest that the flight control system is responding well to any external disturbances or flight path corrections, maintaining an adequate level of control over the UAV's speed.

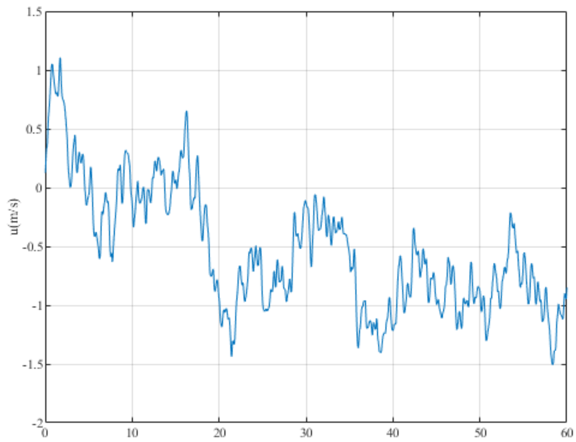

Figure 5. Horizontal velocity of UAV

The w value fluctuates between -0.4 m/s and +0.4 m/s. This represents the vertical velocity of the UAV, or how much it is moving up or down relative to the ground. The small range of fluctuation in **w** indicates that the UAV is maintaining a stable altitude with minimal vertical deviations. It suggests that the UAV's vertical control is quite stable, with effective altitude holding and minimal vertical oscillation. These small oscillations can be attributed to external factors such as minor gusts of wind or small adjustments made by the control system, but they are well within acceptable limits, meaning the UAV is performing its vertical movements efficiently.

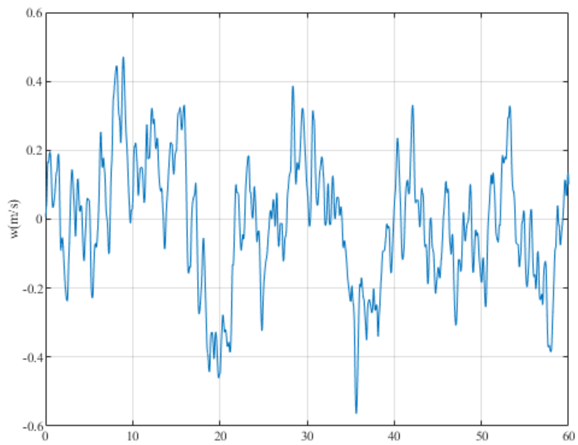

Figure 6. Vertical velocity of UAV

The figure 7 illustrates the pitch rate, q, in response to the applied step input. Initially, the system reacts quickly with a peak pitch rate of approximately 2.5°/s, reflecting its prompt response capability. The pitch rate then settles smoothly within the first 10 seconds, stabilizing near zero. This behavior highlights the system's strong damping performance and its ability to suppress oscillations effectively. The smooth transition to steady-state indicates that the controller successfully mitigates dynamic disturbances and ensures stability in the pitch rate.

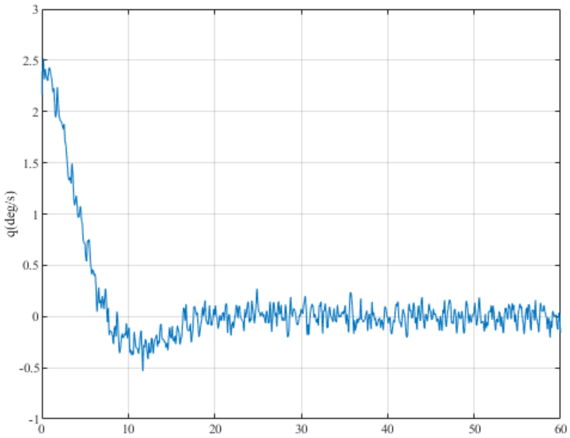

Figure 7. Pitch rate, q, in response to the applied step input

In summary, the results from all three graphs reveal a well-performing control system with fast response times, effective damping, and accurate tracking of the reference pitch angle. The controller successfully stabilizes the pitch dynamics and demonstrates robust performance throughout the test.
In this study, the optimization of PID controllers for unmanned aerial vehicles (UAVs) was carried out using the Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm. The results demonstrated that optimizing the PID controller gains significantly improved the UAV's flight performance. Specifically, improvements in the control of the pitch angle resulted in the controller providing faster and more stable responses. By using the SPSA optimization technique, the proportional (Kp), integral (Ki), and derivative (Kd) gains were successfully adjusted, making the UAV's flight more precise and efficient. The PID parameters obtained through optimization ensured that the system reached the desired state more quickly, with reduced overshoot. The results show that the PID controller optimization greatly enhanced the UAV's control capabilities and increased flight safety. The use of the SPSA algorithm allowed for effective results even in more complex and noisy systems. The optimization, particularly through increased stability, contributed to more efficient and safer flight. Future studies could investigate how these methods perform in more complex flight scenarios and varying weather conditions. Additionally, comparisons of different optimization algorithms and performance evaluations would be valuable for future research.

4. Conclusion

This study examined the optimization of PID controllers for unmanned aerial vehicles (UAVs), with a focus on the use of various optimization techniques, particularly the Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm. The results highlighted the significant role of PID controllers in improving UAV performance, while also emphasizing the need for more sophisticated optimization techniques in more complex and variable flight conditions. The SPSA algorithm emerged as an effective method for finding optimal solutions in noisy and nonlinear systems. A review of the literature showed that SPSA has led to notable improvements in UAV flight control, enhancing PID controller performance and thereby increasing flight safety and efficiency. The optimization techniques used in this study, particularly SPSA, proved to be efficient in achieving faster and more effective performance improvements in UAVs. These findings suggest that SPSA could be a valuable tool for enhancing UAV speed, positioning control, and aerodynamic efficiency. Future research could focus on comparing different optimization algorithms and evaluating their performance in more complex flight environments. Additionally, there is a need for further development of such controller optimizations to enable UAVs to operate effectively in broader operational conditions. In conclusion, PID controller optimization is a key tool for improving UAV flight performance, and the application of modern optimization techniques like SPSA enhances controller effectiveness, enabling UAVs to operate more safely and efficiently.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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A Call for More Detailed Commercial Aviation Statistics in Media Reports

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Abstract

As passenger figures have been growing for several decades and only remarkable economic crises such as the one induced by Covid-19 have been able to slow down this fast growth, the way commercial aviation statistics have been reported by the media has not adapted to the variety of niches filled by airlines, depending on their business models, fleets, services, and routes. Media reports generally provide one key parameter (number of passengers) and, at times, other relevant parameters (number of flights, cargo tonnage) which alone do not provide exhaustive information on the current variability of commercial air traffic. Statistics showing, for instance, the busiest airlines in the world in terms of pure passenger figures are not funded on the core of commercial aviation statistics, such as PKF (passengers kilometers flown), seat configurations comprised of First/Business and comparable classes, *etc*. Another key factor is a number of vital special services provided by legacy carriers which are pretty much neglected by media reports. Via an *excursus* on the issue and tabled estimates on whether the PKF parameter could be used as a general factor of differentiation between different categories of airlines, this paper is aimed at showing how media reports should include a wider range of parameters and provide extra information on the actual complexity of modern-day air travel. Passenger special services (such as those aimed at people whose mobility is reduced) are among the key parameters analyzed for the purpose of this research.

1. Introduction

Passenger air figures have experienced a nearly constant rise for many decades (Budd, 2011; Oxley & Jain, 2015), challenged only by occurrences such as the COVID-19 pandemic (Albers & Rundshagen, 2020). Long-haul *latu sensu* flights have been a factor in air transportation since the very beginning, where the common tendence to perform flights with multiple stops allowed the exact same aircraft types to be involved in short- and long-haul routes (Davies, 1996; Pirie, 2004). At some point, however, these two sub-branches of aviation have become pretty much independent from each other, and affected the market in such a way that newly introduced airplane designs were conceived with either purpose in mind (Cockshutt, 1976; Lanier Benkard, 2004; Cidell, 2006). Before ETOPS (Extended-range Twin-engine Operational Performance Standards), for instance, transatlantic flights were restricted to four-engine aircraft, a minimum requirement that stood for years (DeSantis, 2013). Though these two airliner categories are now independent in operational terms, they are strictly connected from a commercial standpoint as long-haul flights require short-haul routes to for passenger feeding, and *vice versa*, some short-haul routes may be largely maintained by connecting passengers to/from long-haul flights (Cook & Goodwin, 2008; Pels, 2021). The rise of selected narrow-body long-haul routes may lead to a partial overlap in a subset of the broader market (Soyk et al., 2021), but it's worth noting that the wide-body category is also pushing its limits, as Project Sunrise is now demonstrating (Qantas News Room, 2023, web page).

Passenger figures, as well as the number of flights, have been the two dominant key parameters used to define not only the nature and intensity of commercial aviation's growth, but also the broader strategic role of commercial flights in today's society. These two values, especially the former, provide at a glance comprehensive data on the tangible effects of aviation on public mobility so it's not surprising that media reports are generally monopolized by them. Occasionally, these figures have been used as a direct method of comparison between air transportation and other means of public transportation, such as railway systems: a *caveat* on such direct comparison has been highlighted in research decades ago (Hanchet, 1978).

The appearance and consequent success of airlines relying on totally different business models, such as LCCs (Low-Cost Carriers) (Mason, 2005; Warnock-Smith and Morrell, 2008) may have made similar statistics too simplistic to be adequately used as the sole key indicators of air transportation (Graham and Dennis, 2010; Gross and Lück, 2011). By definition, LCCs optimize their flights via lower ticket prices, higher density planes, narrow-body fleets, very high load factors, and networks largely focused on point-to-point short-haul operations (Williams and Baláž, 2009; Vidović et al., 2013). In simple terms, they are set up to be essentially "better" than legacy airlines at carrying higher numbers of passengers (Majerová & Jirásek, 2023). On the other side, legacy carriers have consolidated alliances to counter the direct competition in short-haul markets with expanded networks aimed at feeding towards long-haul routes (Oum and Zhang, 2001). As a direct result of the radical changes experienced by the market in the past few decades, focusing the attention on one parameter that favors one airline category in particular may underestimate the intrinsic complexity of present-day commercial aviation, where different business models exist and fill their own niches. The perception of parameters meant to evaluate airline services has been demonstrated to vary depending on a number of factors (Punel et al., 2019; Zhang et al., 2023).

In addition to the overall optimization aimed at high load factors and high-density seat configurations (Swan, 2002), a considerable change has also occurred in terms of special services, a term that is hereby used to define a number of SSRs (Special Service Requests) which are not universally applied. Many regulations such as the Air Carrier Access Act (ACAA) issued in the United States of America in 1986 added a legal requirement for airlines to allow PRMs (Passengers with Reduced Mobility) to travel. Though the broad category of PRMs is accepted, certain categories of passengers whose mobility is reduced, even today, are allowed – or not – to travel on a per-airline basis (section 3.2), and that in turn leads to an apparent paradox where air connectivity as a whole has increased over the course of several decades (Grubesic et al., 2008; Smyth et al., 2012), but the accessibility of flights to special categories may have not kept the pace with it (Martín-Domingo et al., 2024, *and references therein*). The issue of addressing and reporting the precise percentage of the currently available air transportation network in terms of open accessibility for PRM seems to be a neglected argument in civil aviation (McCarthy, 2011; Warnock-Smith et al., 2023).

A case could be made that some of the above-mentioned issues are the result of airline industry deregulation processes, a significant factor in the general structure of this sector which has been regarded by several authors as not strictly beneficial to the passengers themselves (Thayer, 1982; McHardy & Trotter, 2006; Goetz and Vowles, 2009). Many correlations between the reduction in SSR availability and intense governmental deregulation could potentially be found (Dempsey, 1989), by they're not the primary focus of this research.

This paper is aimed at tackling these issues, which are all but two sides of the same coin, by providing an analysis of the PKF value as well as a review of special services which are generally neglected by a category of airlines, at least among European market leaders. The paper is also aimed at addressing these issues without mentioning directly the airlines that apply certain policies – while this may apparently reduce, at first, the overall amount of content provided by this research and its accuracy, it is deemed a necessary choice meant to maintain this research paper as neutral as possible and allow it to provide insights on commercial aviation which can be applied at all scales from regional to global, even those not covered by this analysis itself.

The implicit goal of this analysis is demonstrating – using the enormous influence of media reports as a *datum* – that their inaccurate description of the civil aviation sector could have deep impacts on society's perception of the aviation market. This assumption is not easy to test – in fact, no clear proof in its favor has been found – but the paper does still provide insights into the real complexity of commercial aviation and the consequent need for media reports to accept a broader range of parameters. What's known for sure is that airlines have learned to use social media as a proper tool to promote their services and provide information to their customers (Heiets et al., 2024), but this is a totally different matter.

Overall, the purpose of this paper is highlighting a gap in academic research on the operational aspects of air transportation and their implications on actual accessibility of air transport for specific categories of passengers, such as PRM. The work is also aimed providing a tangible example of data analysis demonstrating that the parameters normally used for comparisons between airlines in media reports and other contexts may not be representative of the broad complexities of air travel in the global economy. In fact, airlines do have various degrees of popularity depending on their on time performance, customer services, and general figures: this work, although generic in nature, is set to demonstrate that the public may be missing key aspects of the general picture, and that in turn may drive future research to perform additional assessments of these factors which may be used by regulators and policy makers to improve the global airline market.

The article is divided as follows: section 2 describes the methods used in the statistical evaluation; section 3 shows the results of data evaluation and provide an operational review of a number of key services mentioned in the paper; section 4 is aimed at discussing the results.

2. Methods

The true complexity of commercial aviation statistics is hereby analyzed for the purpose of this research, starting from the PKF parameter (Passengers Kilometers Flown) as an overly underrepresented source of differentiation between different types of aircraft operations. In fact, past research has frequently emphasized the importance of these parameters as airline efficiency indicators (Encaoua, 1991; Cui and Li, 2017; Cui and Yu, 2021). One of the intended goals is testing whether the PKF alone is a sufficient tool for airline category differentiation. A nearly identical parameter, RPK (Revenue Passenger Kilometers), is hereby mentioned but will not be discussed any further as its core difference with PKF is the restriction of applicability to revenue passengers (thus excluding positioning crew and similar categories of non-paying pax). Though RPK may be more appropriate, from now on in the article the PKF value alone will be evaluated.

That said, PKF hides an intrinsic sub-differentiation that this article will attempt to underline and remark, as it's strictly connected to the main scopes of this research. In purely mathematical terms, the official definition of PKF for any flight x is the result of multiplication between the number N of passengers carried by flight x and the mileage M of the flight itself, via a straightforward linear equation:

$$PKFx = Nx * Mx \qquad (Eq. 1)$$

The parameter implies that what is normally regarded as the only main factor of commercial transportation by media reports, the number of passengers N, is weighted depending on the mileage of operated routes. Two flights carrying the exact same amount of passengers N, one covering a mileage M_1 of 800 kilometers and the other covering a different mileage M_2

of 6.000 km, will have different PKF values PKF_1 and PKF_2, with $PKF_2 > PKF_1$ by a factor that is proportional to the ratio between M_2 and M_1. For example, provided that $N_1 = N_2 = 200$ pax, the results would be $PKF_1 = 160.000$ and $PKF_2 = 1.200.000$, where the *Y/X* ratio yields the same result as M_2/M_1: *7,5*. Though these calculations seem – and indeed are – extremely basic, they're apparently ignored by the gross majority of public media aviation reports.

A comparison between PKF and N will be used for three distinct scenarios, each covering a generic type of aircraft operation and a fixed number of daily flights, to remark the differences between these values and further analyze differences in the main reported subsets of each category. The values are not randomized via Monte Carlo evaluations as they would have added an unnecessary degree of variability to the calculation – instead, recurring averaged values will be used to simulate one week of operations. The graph (Figure 1) is computed via R v. 4.3.3, using the Gpplot2 package and its respective library.

The second part of section 3 will review a number of special services, each with a brief description of their features and importance, and a remark on their neglection by media reports on commercial air traffic. These services are listed by their IATA codes.

3. Results and Discussion

The paper is aimed at addressing two branches of the proposed issues via multiple approach. Section 3.1 covers PKF and N values, while section 3.2 reviews special services.

3.1. Evaluation of simulated N and PKF values

The direct comparison of the previously described numerical parameters is hereby evaluated. Table 1 provides detailed figures on a number of key parameters, classified by category, while Figure 1 plots these parameters. Table 2 and 3 describe alternate values of selected data compared to Table 1.

Three main families of scenarios have been covered: long-haul operations have been restricted to two daily flights, while short-haul operations cover the range between six and eight daily flights. Six and eight flights are compatible with four routes served on a daily basis; seven flights cover the first scenario, plus an extra flight to an airport distinct from the primary base of operations. Realistically, this could be intended as an average between six and eight daily flights that would propagate over the course of one week or more, as short-haul operations may indeed vary from that point of view.

Narrow-body mileage values have been fixed at a value of 800 km per flight, while narrow-body mileage have been set to 7.000 km. Two hypothetical seat configurations have been considered for each of the two categories: multi-class and high-density single class. These configurations are deemed hypothetical and plausible for the aircraft types falling into each broad category – any reference to an actual configuration used by any airline is to be considered coincidental. In literature, the topic of seat distribution between two or more distinct classes has been a relevant focus of research in the field of airline industry management (Teichert et al., 2008); various optimal configurations have been proposed and tested, and their ratio has been demonstrated to depend on specific factors such as the market these flights are meant to operate in, seasonality, fuel cost and consumption efficiency, *etc.* (Kypasiris & Koulamas, 2018, *and references therein*). In this research paper, plausible two- and three-class configurations are used in data evaluation.

F stands for First Class, J stands for long-haul Business Class, C stands for short-haul Business Class, and Y stands for Economy. Research has highlighted the importance of additional classes such as Premium Economy especially for the long haul sector, however PE is excluded from this evaluation due to its minor impact on cabin density compared to First and Business (Hugon-Duprat and O'Connell, 2015). The four aircraft types have been identified with the letters A through D, as described into the details by Table 1. Load factors have also been fixed at a single value of 87.5%. This value was based on a performance report by IATA issued in 2017, plus an adjustment accounting for load factor optimization in the following years. Furthermore, averages in load factors are frequently used in research to assess the cost efficiency of business models and specific routes (Atasoy et al., 2013, *and references therein*). Three distinct business models are being considered: LCC, Legacy, and "Hybrid" with respect to high-density long-haul operations, as this growing niche of air travel retains characteristics of the other two categories (Albers et al., 2020).

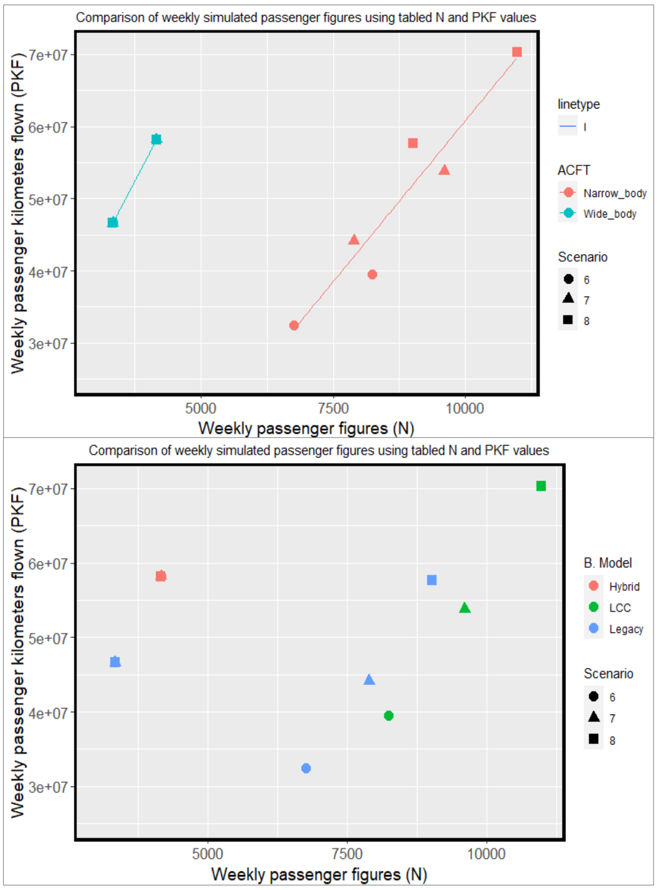

Figure 1. A: Graph showing a direct comparison between N and PKF values over the course of one hypothetical week of operations, using data from Tables 1-3. The colors differentiate between aircraft type while the symbols cover the three reported scenarios of 6, 7, and 8 daily flights operated by narrow-body aircraft (note that in the case of wide-body aircraft, they overlap as they're not affected by these changes). Daily data are not graphically shown because they would retain the exact same patterns. B: same graph, but the main factor of differentiation is the business model.

Table 1. Comparison of passenger values between four distinct categories. A = narrow body, high density seating, c.a. 8 daily flights (4 routes); B = narrow body, multi-class seating configuration, c.a. 8 daily flights (4 routes); C = wide body, multi-class seating, c.a. 2 daily flights (1 route); D = wide body, high density seating, c.a. 2 daily flights (1 route).

Category / Parameters	A	B	C	D
Seats	225Y	20C + 170Y	10F + 20J + 250Y	350Y
Business model	LCC	Legacy	Legacy	Hybrid
Average load factor	87.5%	87.5%	87.5%	87.5%
Daily flights	8	8	2	2
Daily mileage (km)	6400	6400	14000	14000
Daily passengers (N)	1528	1288	476	594
Daily PKF	10035200	8243200	6664000	8316000
Weekly flights	56	56	14	14
Weekly mileage (km)	44800	44800	98000	98000
Weekly passengers	10976	9016	3332	4158
Weekly PKF	70246400	57702400	46648000	58212000

Table 2. Same figures as in Table 1, with the number of daily flights operated by narrow-body aircraft set to 7.

Category / Parameters	A	B	C	D
Seats	225Y	20C + 170Y	10F + 20C + 250Y	350Y
Business model	LCC	Legacy	Legacy	Hybrid
Average load factor	87.5%	87.5%	87.5%	87.5%
Daily flights	7	7	2	2
Daily mileage (km)	6400	6400	14000	14000
Daily passengers (N)	1528	1288	476	594
Daily PKF	7683200	6311200	6664000	8316000
Weekly flights	49	49	14	14
Weekly mileage (km)	39200	39200	98000	98000
Weekly passengers	9604	7889	3332	4158
Weekly PKF	53782400	44178400	46648000	58212000

Table 3. Same figures as in Table 1, with the number of daily flights operated by narrow-body aircraft set to 6.

Category / Parameters	A	B	C	D
Seats	225Y	20C + 170Y	10F + 20C + 250Y	350Y
Business model	LCC	Legacy	Legacy	Hybrid
Average load factor	87.5%	87.5%	87.5%	87.5%
Daily flights	6	6	2	2
Daily mileage (km)	6400	6400	14000	14000
Daily passengers (N)	1528	1288	476	594
Daily PKF	5644800	4636800	6664000	8316000
Weekly flights	42	42	14	14
Weekly mileage (km)	33600	33600	98000	98000
Weekly passengers	8232	6762	3332	4158
Weekly PKF	39513600	32457600	46648000	58212000

Though the reported simulations have a *caveat* due to the variability of the described factors, they fulfill the intended purpose of providing a range of results that help covering the complexity of N and PKF parameters under different circumstances. Figure 1A and B sums up graphically the main differences, while the three tables provide numerically very interesting clues on the intrinsic complexity of commercial aviation figures. Hereby listed are the main results of the simulations:

1) With single flights being taken in consideration, long-haul operations yield higher passenger figures and much higher PKF values compared to their narrow-body counterparts;

2) Cumulative daily figures show fewer passengers being carried by wide-body aircraft under all circumstances. PKF rankings report a shift: with 6 daily narrow-body flights, wide-body aircraft still dominate the cumulative daily PKF; with 7 flights, the long-haul high-density configuration alone (D) maintains that dominance, while the three-class configuration (C) is now ranked 3rd; with 8 flights, A ranks 1st, C ends up 4th, while B and D report similar figures (8.243.200 and 8.316.000, respectively);

3) Weekly performances maintain lower passenger figures for wide-body aircraft, while in terms of PKF, the dominance of wide-body aircraft is limited to the 6-flights scenario, while in the 7-flight scenario category A ranks 2nd behind D. In the 8-flight scenario, A dominates in terms of PKF, but D still ranks 2nd, and C now reports the lowest value.

Therefore, the simulations indicate that intense enough short-haul operations (7-8 daily flights) operated by narrow-body aircraft can indeed compete with long-haul operations operated by wide-body aircraft, even if PKF values are considered, and this adds up to the complexity of commercial aviation figures mentioned at the beginning of the article. One preliminary conclusion of this research is that the PKF value alone is not sufficient as a tool of differentiation.

Also, it's worth noting that no corrections have been applied in order to make up for capacity reductions caused by Business and First class seats, which by definition tend to occupy more volume in the cabin, thus affecting pure passenger figures. Though the capacity to offer such services is indeed a remarkable indicator of an airline's service standards (Brochado et al., 2019), and the average cost of such tickets is demonstrably higher than that of Coach and comparable classes, this paper will not apply any corrections, as the reported differentiation between seat configurations is deemed enough to show how N and PKF performances vary across the market.

3.2. Special services review

This section of the work will focus specifically on a number of key special services that are deemed, for the purpose of this research, of strategic importance, yet they are subject to general neglection in media report coverages as well as by leading LCC airlines in the European market, which in this case is used as a sample of the global aviation market. Furthermore, they appear to be all but neglected even in the context of academic research on commercial aviation, as a search for any papers via the IATA codes of these services, at the time of writing this research paper, yielded no results whatsoever. Please note that these are not the only special services available – the actual list of services is much longer and covers a number of very specific circumstances and requirements. The difference between these services and other services which are generally provided on a global scale by aviation lies on the specificity of their setting, as they normally require precise cabin seat configurations, hold configurations, ground equipment, *etc*. Broadly speaking, their applicability is airline category dependent.

AVIH (Living animal in hold). As more attention is focused globally on animal rights, and pets have gained access to more services thanks to the pressure and effort of entire associations devoted to the topic of enhanced synergy between humans and pets in numerous environments, the aviation sector also frequently covers the need to travel with animals up to the size of large dogs. However, loading a living animal into an aircraft hold requires time, special care, specific equipment, and pressurized hold, all requirements that may not match generic LCC practices, though exceptions can occur. Please note that this service is related to PETC, with the size and nature of the pet being the main difference between the two services and codes.

DEPO category of deportees (divided into DEPA, Accompanied, and DEPU, Unaccompanied). Deportees are passengers whose names are hidden from DCS (*Departure Control Systems*, the programs used at airports for ground handling management and operations, including passenger acceptance procedures), as only law enforcement and similar entities have access to specific details on them. The fact itself that their true identity is hidden is a relevant insight on the security concerns related to them. The difference between DEPA and DEPU could be broadly summarized as a difference in terms of security measures, because the -A deportees require an escort (which is generally equipped with authorized firearms) while the -U deportees don't. This service is of strategic importance, because transportation by air of individuals that need to be transferred from two distinct locations is safer compared to other means of transportation, especially in terms of security concerns.

HUM (Human remains). Another poorly "advertised" service is the transport, as cargo, of human remains that would otherwise require time consuming and logistically challenging alternate means of transport.

PETC (Pet in Cabin). Similar to AVIH in the general sense, but the transportation in cabins instead of holds comes with a different set of issues that may be addressed, such as limitations on the number of PETC allowed onboard, their seating policies and the size of their animal carriers.

STCR (Stretcher). Perhaps the most articulated special services of all, the stretcher service required *ad hoc* adjustment to cabin configurations to take place. In fact, several rows have to be reclined and modified ahead of the flight to accommodate a stretcher, and that requires advance booking as the overall capacity of the cabin in terms of offered seats is lower.

UMNR (Unaccompanied Minor). Children traveling without their families or any individual that is legally authorized to accompany them and take full responsibility throughout the travel, are considered unaccompanied minors and require a special service be implemented, which involves personnel from ground handling companies as well as the airlines themselves. The service increases in complexity should the journey involve one or more connecting flights. Without this service, an authorized family member or tutor would be forced to fly with minors.

4. Conclusions and Perspectives

The performed analyses, though straightforward in their extent and purpose, clearly demonstrate the intrinsic differences between airlines in terms of seat configuration, fleets, served networks, and said differences are not adequately reported by media. Limiting the evaluation to hypothetical seat configurations, routes, and load factors, without indicating specific examples from present-day airline network, has still allowed the paper to provide new insights on aspects of commercial air transport which are generally ignored by academic research. Though the assumption by which regulators may be influenced by limited statistics when making strategic decisions may not be proved unless clear statements going in that direction are issued, it's safe to assume that the broader public is not instructed on the complexity of air transportation and its numerous niches. In particular, it's safe to claim that the media coverage on strategic special services offered to passengers by specific types of airlines is not adequately covered, thus resulting in an incomplete perception of said airline type for the general public.

Media reports could therefore be issued in a more professional way, one that could explain the importance of commercial aviation's variety, which by its very nature goes beyond the mere concept of how many passengers are being carried and how many flights are being operated. With enhanced statistics, it may be possible to differentiate between categories and therefore give proper context to the high variability of commercial air transportation.

Future research, possibly aimed at specific markets, could pinpoint discrepancies in terms of SSR coverage to the general public, especially in the case of passengers whose mobility is reduced (PRMs). These discrepancies could be highlighted at various scales, ranging from specific routes to the entire set of flight connections between two countries. Regulators and policy makers could, at that point, introduce new requirements aimed at a proper balance in the market between reduced ticket prices and accessibility to a wider range of passenger categories.

Appendix

An upscaled version of Figure 1 is issued as Appendix.

Ethical approval

Not applicable.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper. Furthermore, the author would like to specify that this research paper is an independent endeavor, unrelated to the affiliated institutions - hereby mentioned only for the sake of completeness – their views, policies and research perspectives.

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Decoding User Reviews for Low-Cost Airlines Marketing: A Global Analysis of Passenger Preferences

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Abstract

The airline industry is a key component in the transportation and tourism sectors thanks to its economic potential and global scope, and the complex structure of customer preferences, competitive environment, and changing dynamics require examination of the marketplace. In this context, it has been determined that many studies have focused on user studies in the airline market, while only a few studies have examined the Low-cost airline sub-context in the airline market. This study aims to investigate the factors affecting consumer recommendation and rating scores through user reviews in the context of Low-cost airlines. In the study, regression analyzes and difference tests were used on 5672 user reviews on airlinequality.com about 20 airline brands on Skytrax's World's Best Low-cost Airlines 2023 list. In the regression analysis, it was seen that value for money was the most important determining factor in recommendation status and rating scoring, followed by ground service, cabin crew service, seat comfort and food and beverage variables. Difference tests reveal that solo leisure travelers tend to rate and recommend higher. It is also concluded that first-class passengers using LCC airlines have higher tendency for rating scores higher and recommending.

1. Introduction

In the Web 2.0 era (O'reilly, 2009) and beyond, web users began communicating with each other in two-way ways and began to influence other users by sharing their opinions. In previous years, marketing communication in the form of messages conveyed by companies to consumers as "announcements" has now become a form in which consumers interact with both the company and other consumers. Today's internet users spend an average of 6 hours 37 minutes of their day on the internet (We Are Social & Meltwater, 2023). In parallel with the increase in the time users spend on the internet, the variety and intensity of the content they share with other users have increased in recent years. Today's consumer uses the web for a broad range of different purposes, such as finding information, staying in touch with friends and family, keeping up to date with news and events (We Are Social & Meltwater, 2023). They also consume the content, participate in discussions, share information, and affect others' actions (Heinonen, 2011). These developments require understanding the type and content of consumers' online communications with each other and with brands.

As consumers' interaction with brands and other consumers increases, the reviews written by consumers on digital platforms have become important. Through these reviews, consumers can share their positive/negative opinions and experiences about products and services with thousands of users. On the consumer side, online reviews help consumers obtain product information and alleviate uncertainties before the purchase decision (Yan et al., 2015). For the company side, online reviews can help understand the customer and the market in several industries, such as movies (Duan et al., 2008), retail (Floyd et al., 2014), healthcare (Abirami & Askarunisa, 2017), cosmetics (Haddara et al., 2020). Tourism is one of the industries highly affected by the COVID-19 pandemic, as international tourist arrivals dropped to 406 million people in 2020 worldwide. However, the effect of COVID-19 disappeared over time as the increase to 1.286 billion people (33.9% increase between 2022 and 2023) took place (UNWTO, 2023). Within the landscape of online review analysis, the tourism sector presents a critical potential due to its experiential characteristics and the ability of consumers to influence each other.

The airline industry is one of the significant areas where competition is intense with different customer segments and product/service groups within the scope of tourism (Aydın, 2024; Duran et al., 2024). Different types of airline business models, such as full-service and Low-cost airlines, have emerged to meet the needs of different customer groups in the airline market. Low-cost airline companies "*offer lower fares to attract passengers by reducing their service costs by means such as reducing free in-flight services, standardizing airplane fleet and cabins, increasing luggage restrictions, and using secondary airports*" (Chang & Hung, 2003). IATA (2022) report indicates that even though LCC companies carry more passengers than network carriers in the intra-European market, network carriers have increased market share by 9% with the help of higher maintained service levels. Thus, service levels and market perception of these levels are essential tasks for LCC marketing decision-makers.

The primary rationale for the study is to provide the information necessary to develop more effective strategies to increase user experience and satisfaction in the airline industry. This study conducts a multidimensional analysis by examining the factors affecting the effectiveness of user recommendations and the impact of these factors on rating scores using online data. In this way, it provides a better understanding of the main motivations that shape users' evaluations and adopts a more comprehensive analysis approach by combining big data (online user reviews) and quantitative data (consumer surveys). In addition, the study focuses on the low-cost airlines (LCC) sector, in particular, by conducting a more in-depth examination of this sector's unique dynamics and user expectations. This reveals its originality by offering more specific recommendations for the individual needs of the LCC sector. The study uses a current dataset (Skytrax World's Best Low-Cost Airlines 2023 list) to reflect the sector's most current trends and user expectations. Analyzing this list can guide current sector dynamics in the airline sector. For these reasons, the study reveals its originality in contributing to the airline literature and leading marketers in the airline sector.

This study set out to examine LCC passengers in an online review context to identify the specific points of user recommendations through a variety of determinants. The first research question focuses on the factors regarding the user recommendation activity in the online review, while the latter one examines the rating score with determinants. Dalla Valle and Kenett (2018) highlight the value of integrating big data and customer surveys for better understanding in their study. This study follows that approach and chooses the top Low-cost airline companies in Skytrax World's Best Low-cost Airlines 2023 list (Skytrax, 2023), including the brands selected through customer surveys, and integrates the online review data (Skytrax user reviews on airlinequality.com) as the sample for the study. Employing a dataset obtained for the LCC airline companies with a regression analysis helps to explore the user motivations in the airline industry for the specific context.

2. Theoretical Framework

In the conceptual framework of the study; information about electronic word of mouth and user comments, eWOM in the airline market is given.

2.1. Electronic word of mouth and user reviews

Consumers live in communities and societies and affect each other through communication and activities. This phenomenon leads to word of mouth (WOM) being a fundamental concept in consumer research. According to Westbrook (1987), WOM refers to the informal communication activity between consumers on the topics of ownership, usage, and characteristics of specific products/services and their sellers. With the emergence of increasing technology and digital platforms in recent decades, the concept of WOM has also been shaped and evolved into a new dimension in the form of electronic word of mouth (eWOM). Defined as "any positive or negative statement made by potential, actual, or former customers about a product or company, which is made available to a multitude of people and institutions via the Internet" by Hennig-Thurau, Gwinner, Walsh & Gremler (2004), e-WOM is a determinant factor for the consumer decision-making in the online context. Consumers, who were previously able to communicate with relatively limited circles in the WOM era, can now influence thousands of people over the web with the help of the internet and social media channels in the eWOM era. In this regard, marketing decision-makers focus on eWOM to better understand consumer behavior and the market.

The multifaceted nature of the eWOM concept includes several aspects for business decision-makers. The first aspect refers to justifications for producing content for eWOM. Web users generate content for eWOM for a wide range of reasons, including reputation, sense of belonging, and enjoyment of helping other consumers (Cheung & Lee, 2012). The second aspect is about the rationality of trusting in communications. Relying on WOM communication contains a basic idea, as people have more credible perceptions about them and evaluate WOM communication as "people like me" (Allsop et al., 2007). The third aspect represents the conceptual structures associated with the eWOM concept. According to Cheung and Thadani (2012), the eWOM concept is related to stimuli-related factors (argument quality, valence and so forth), receivers-related factors (involvement, prior knowledge), communicators-related factors (expertise, trustworthiness, attribution), contextual factor (platform) and responses (eWOM adoption, purchase intention and so forth). Understanding the basic ideas and broad scope of eWOM is an essential start to marketing decision-making.

The effect of eWOM on business operations includes several consequences for marketing decision-makers. The first reality refers to consumers' expressions and the effect on the purchases, as the consumers' expression of satisfaction/dissatisfaction through product review pages can be an indicator of information for others and can influence the purchase decisions of potential customers (Liu et al., 2023; Wang et al., 2023a). This reality is reflected in the product/service sales amount. As another consequence, online reviews are found to be an indicator of product/service levels (Zhu & Zhang, 2010; Cui et al., 2012; De Maeyer, 2012). The cycle between satisfaction/dissatisfaction and sales amount and indication of product/service level refer to a basic level idea for brand managers. However, the facets of the content and the long-term effects of brand-related factors have crucial effects on decision-makers, leading to the necessity of updating brands' marketing strategies to more comprehensive levels on these perspectives (Oh & Park, 2020; Wang & Chan-Olmsted, 2020).

Tourism and hospitality are among the most critical industries in which the eWOM concept is highly effective. As consumer evaluations and sales volumes are critical in the industry, user reviews are used to understand the marketplace from customers' perspectives. Several studies (Sotiriadis & Van Zyl, 2013; Harris & Prideaux, 2017; Kanje et al., 2020; Filieri et al., 2021) examine the eWOM concept and various sub-contexts within the industry promise the new research avenues. The subsequent section focuses on the eWOM concept in the airline industry, where consumer preferences are highly affected by individual choices and are open to other users' ideas expressed in offline or online channels.

2.2. eWOM in airline market

While the airline industry presents similarities to other tourism contexts in terms of consumer preferences being influenced by individual experiences and other users' reviews, still has unique characteristics. According to Leong et al. (2015), airline companies need to provide reliable products and services to customers; as the airline industry includes intense competition, they could have significant problems unless they fulfill this side. The crucial part of staying competitive in the airline industry is identification of the choice criteria of customers formulating marketing segmentation and promotional strategies using that information (Chen & Chao, 2015). For the customer side, staying competitive is related to customer satisfaction. According to Park, Robertson & Wu (2004), the level of passenger satisfaction and value perception are related to meeting the customers' expectations. From this point of view, airline companies need to evaluate user-generated eWOM content on the web to better understand customer expectations and integrate this perspective into marketing decision-making.

The significant potential of user reviews highlights the importance of harnessing user reviews for decision-making. Lee & Yu (2018) indicate that online reviews can serve as a reliable substitute for airport service quality ratings and can also be used for validating the results of conventional industry standard survey results. Processing user reviews represents a different approach than collecting data from users through surveys and using tools such as SERVQUAL in previous years. Li, Mao, Wang & Ma (2022) call the approach as "crowdsourcing" and conclude the possibility of obtaining the thoughts/concerns from large group of passengers which leads to better problem-solving and identification of improvement areas. Considering the volume and complexity of user reviews, a comprehensive analysis is imperative to comprehend the diverse range of topics included within the discourse.

For a comprehensive analysis of the discourse, user reviews on digital platforms need to be transformed into meaningful results for marketing decision-making. In the first approach, classical correlation and regression models can be followed since review data in Skytrax (airlinequality.com), like websites, include numerical values. For example, Wang, Zheng, Tang, & Luo (2023b) employ the sentiment analysis and use the extracted emotions to study for the recommendation intention variable in Skytrax reviews. In the second approach, a decoding process takes place. Several methodologies such as sentiment analysis (Song et al., 2020), latent semantic analysis (Sezgen et al., 2019), and topic modeling (Kwon et al., 2021; Farzadnia & Vanani, 2022) are used in previous researches to decode the passenger/market preferences from raw data. Approaches can employ different levels for data decoding. Using the macro-level approach, Punel, Hassan & Ermagun (2019) use online reviews to evaluate the differences among passengers from different geographical regions. On the other hand, using the micro-level approach, Bogicevic, Yang, Bilgihan & Bujisic (2013) employ the travelers' comments in their study and reveal satisficers-cleanliness and pleasant environment to spend time in - and dissatisfiers-security-check, confusing signage, and poor dining offer-in their study.

Examining the effects of airline passenger types, travel types, and cultures is essential for airline marketing. Sezgen, Mason & Mayer (2019) conclude that drivers of passenger satisfaction have differences regarding the air travel class (Low-cost or full-service carrier) in their study. In another study, Lim & Lee (2020) examine the service quality perceptions of full-service carrier and Low-cost carrier passengers and conclude reasonable differences. The authors assess the topics and deduce that tangible dimension is the most significant dimension for full-service carrier customers, while reliability dimension is the significant dimension for Low-cost carrier customers. The characteristics of different types of airline customers can reflect different outcomes or emphasize different preferences in the airline industry. This study focuses on Low-cost carrier airline companies in specific, to examine users' recommendations with the determinant factors.

3. Methodology

3.1. Data collection

Tourism users on web share their experiences with other users through several channels such as Tripadvisor, Booking.com, Skytrax, while they target specific audiences in the marketplace. Skytrax (https://skytraxratings.com/) (Skytrax, 2024) is one of the specific website for the airline industry containing the user reviews regarding the flight experiences. This study uses airlinequality.com data for user reviews regarding airline industry. World's Best Low-cost Airlines 2023 list (Skyrtax, 2023) is employed for the sampling decision regarding companies and 20 airline companies are selected for the study sample. The company names are listed as AirAsia, Scoot, IndiGo, Flynas, Volotea, Transavia France, Sun Country Airlines, Southwest Airlines, airBaltic, Jet2.com, EasyJet, Vueling Airlines, Ryanair, Jetstar Airways, flyDubai, Peach, JetSMART Airlines, Jetstar Asia, Eurowings, SKY Airline.

Within the scope of the data collection, 12,939 passenger reviews and rating information were obtained from the Skytrax user reviews website (https://www.airlinequality.com). Data collection took place on 10 October 2023 and the Python programming language (Rossum, 1995) is employed for retrieving the review data and the range of reviews is between April 2015 and September 2023. 8.515 user reviews in the initial dataset were removed due to some missing user ratings. 5.672 user reviews are used as the sample of the study. SPSS package software is used for analysis (Verma, 2012).

3.2. Study sample

The variables regarding the review unit in the dataset includes seat comfort, cabin staff service, food & beverages, inflight entertainment, ground service, wifi & connectivity, value for money, recommended status and overall rating. Recommended status and overall rating are used as dependent (shown as green color in Figure 1), the former variables are used as independent variables (shown as yellow color in Figure 1). The variables in the dataset also contains traveler type and seat type information (shown as blue color in Figure 1) which are used for difference tests.

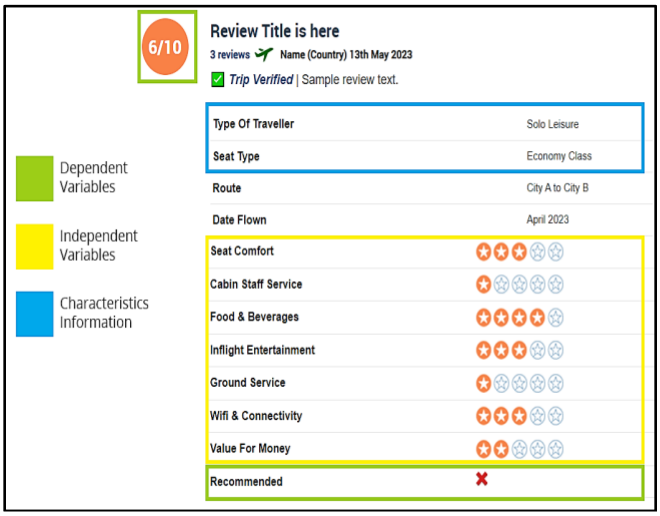

Figure 1. Online review sample for hypothesis testing
Source: Created by the authors.

Perceived value is an assessment made by a consumer regarding how much benefit they receive in return for a product or service. This assessment is related to the emotional, social and psychological benefits of the product as well as its physical properties. Therefore, the hypotheses addressing the perceived value of consumers are stated below (Zauner, Koller & Hatak, 2015).

H_1: The users' rating scores regarding seat comfort, cabin staff service, food & beverages, inflight entertainment, wifi & connectivity, ground service and value for money affect recommend status of the user.

H_2: The users' rating scores regarding seat comfort, cabin staff service, food & beverages, inflight entertainment, wifi & connectivity, ground service and value for money affect users' rating scores.

The hypotheses developed below are based on the expectancy-evaluation theory of attitude, which argues that a consumer's attitude toward a service is based on his or her expectations or beliefs about the service's relationship to other services (Alexander, 1976).

H_3: There are statistically significant differences in rating scores between traveler types.

H_4: There are statistically significant differences in rating scores between seat types.

The hypotheses generated according to social identity theory, which is presented to explain intergroup behavior and intergroup communication based on the intrinsic value that consumers place on their social group memberships and their desire to see certain social groups in a positive light, are presented below (Harwood, 2020).

H_5: There are statistically significant differences in recommendation statuses between traveler types.

H_6: There are statistically significant differences in recommendation statuses between seat types.

3.3. Descriptive stats

Independent variables are scored by star ratings and can have values between 1-5 in the user reviews. The descriptive stats of independent variables are presented in Table 1 which indicates the average values for all independent variables between 2.25 and 2.84. The average values for these variables are consistent to LCC airlines context of this study.

Table 1. Independent variable descriptive stats

Variables	Minimum	Maximum	Mean	Std. Deviation
Seat Comfort	1	5	2.46	1.377
Cabin Staff Service	1	5	2.84	1.569
Food & Beverages	1	5	2.32	1.390
Inflight Entertainment	1	5	2.25	1.253
WiFi & Connectivity	1	5	2.36	1.234
Ground Service	1	5	2.45	1.565
Value for Money	1	5	2.63	1.616

Characteristics information about users are presented in Table 2. According to table, 32.7% of users have solo leisure type, 31% of them have couple leisure, 23.8% of them have family leisure, and only 12.5% of them have business travel type. Travel class ratios is consistent with LCC airline context, as economy class has the majority (93.4%) travel classes of users.

Table 2. User characteristics descriptive stats

Variables	Subgroups	Frequency	Percentage (%)
	Solo Leisure	1854	32.7
Travel Type	Couple Leisure	1758	31.0
	Family Leisure	1352	23.8
	Business	708	12.5
	First Class	13	0.2
	Economy Class	5296	93.4
Travel Class	Business Class	182	3.2
	Premium Economy	181	3.2
	Total	5672	100

4. Result

4.1. Logistic regression analysis for recommendation status

Logistic regression is a statistical model that estimates the probability of an event occurring. In this model, the probability of an event occurring is examined when the dependent variables are binary or categorical (Hosmer & Lemeshow, 2000). In this context, in the research recommendation status is included in user reviews in two states (Yes and No); logistic regression methodology is employed in the first part of the analysis, consistent to the binary nature of dependent variable. The dependent variable for logistic regression analysis is recommendation status; while the independent variables are: seat comfort, cabin staff service, food & beverages, inflight entertainment, wifi & connectivity, ground service and value for money. Wald, Omnibus and Hosmer-Lemeshow tests and correct classification rates are mostly used to examine the goodness of fit of the binary logistic regression model in the research (Oktay & Orçanlı, 2014).

Below is the table showing that the model is statistically significant ($p < 0.01$) according to the Omnibus model.

Table 3. Omnibus tests of model coefficients

	Chi-square	df	Sig.
Step	5777.515	7	.000
Block	5777.515	7	.000
Model	5777.515	7	.000

The goodness of fit results are given in the table below and the reference category is shown as the "do not recommend" category.

Table 4. Determination of reference category

Original Value	Original Value
I recommend	1
I no not recommend	0

The Cox & Snell R2 value, which shows the rate at which the independent variables explain the variance in the dependent variable in the model, and the Nagelkerke R² value, which is a relationship test measurement method developed to ensure that the Cox and Snell R² statistics take values in the range of 0-1 (Kalaycı, 2010), are presented in the table below.

Table 5. R^2 values of the model

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	1644.109[a]	.639	.875

According to Table 5, the Cox & Snell R2 value for the model is 0.639, which means that the independent variables explain 65.9% of the variance in the dependent variable. The Nagelkerke R² value for the model is 0.875, which means that the dependent variables explain 87.5% of the variance in the dependent variable.

Table 6 shows the prediction accuracies for the analysis and indicates that prediction accuracy regarding "Not recommended" status is 92.2, while for "recommended" status is 96.2 and for the whole model prediction accuracy is 94.7.

Table 6. Correct classification ratio table of recommendation model

		Predicted		
		Recommended		Percentage Correct
Observed		Yes	No	
	No	1890	160	92.2
Recommended	Yes	138	3484	96.2
				94.7

The classification table is used to evaluate the goodness of fit of the model and the other method used to test the significance of the model is the Hosmer-Lemeshow test. The Hosmer-Lemeshow test statistic, an important measurement method used to test the logistic regression model, tests whether all logit coefficients outside the constant term are equal to zero. Indicated as "H_0" hypothesis, $\chi2$ values of the Hosmer-Lemeshow test statistics are calculated and included in Table 7. The hypotheses for this test are;

H_0: The parameters exhibit discrimination in terms of predictive power.

H_1: The parameters do not exhibit discrimination in terms of predictive power.

Table 7. Hosmer and lemeshow test

Chi-square	df	Sig.
17.942	8	.122

Table 7 indicates that the model is adequate model with a good fit (Chi-square: 17.942, df: 8 and $p > 0.05$) and H_0 hypothesis is supported which means that the parameters exhibit discrimination in terms of predictive power.

The observed and expected frequencies needed to calculate the Hosmer-Lemeshow test statistics and the Hosmer-Lemeshow test are included in Table 8. The data in dependent variable (recommendation status) is divided into ten groups and it is concluded that the observed and expected values are close to each other, which represents the model fit indicator.

Table 8. Contingency table for Hosmer and Lemeshow test

		Observed	Expected	Observed	Expected	Total
Step 1	**1**	663	665.389	3	0.611	666
	2	563	565.236	3	0.764	566
	3	565	565.062	2	1.938	567
	4	565	562.736	3	5.264	568
	5	554	550.340	13	16.660	567
	6	483	483.453	84	83.547	567
	7	193	195.749	375	372.251	568
	8	30	27.947	537	539.053	567
	9	5	4.981	563	563.019	568
	10	1	1.107	467	466.893	468

Table 9 includes the information of expected coefficient **(β),** standard error of expected coefficient (SE**β),** Wald values, 95% confidence limits and significance values (Sig.) for the expected odds ratio. Examination of Wald values shows that seat comfort, cabin staff services, food & beverages, ground service, value for money variables have higher values than 2.

Table 9. Binary logistic regression analysis results

	β	Std. Error (β)	Wald	df	Sig	Exp (β)	95% C.I.for EXP(B) Lower	95% C.I.for EXP(B) Upper
Constant	-	-	-			-		
Seat Comfort	0.427	0.066	42.214	1	0.000	1.533	1.348	1.348
Cabin Staff Service	0.526	0.061	75.051	1	0.000	1.693	1.503	1.503
Food & Beverages	0.257	0068	14.440	1	0.000	1.293	1.133	1.133
Inflight Entertainment	0.085	0.065	1.707	1	0.191	1.088	0.958	0.958
Wifi	0.063	0.065	0.940	1	0.332	1.065	0.938	0.938
Ground Service	0.662	0.053	157.181	1	0.000	1.938	1.748	1.748
Value for Money	1.355	0.064	441.683	1	0.000	3.875	3.415	3.415

It is concluded that the seat comfort of airline passengers (β:0.427, $p<0.05$) significantly affects the passengers' recommendation for airline travel. The positive *β* value indicates that seat comfort increases passengers' likelihood of recommending activity. Passengers who recommend air travel are 15.33% more likely to perceive seating comfort than passengers who do not recommend air travel. The second finding of the table shows that cabin staff service has a significant and positive effect on passengers' recommendation of the airline (β:0.526, $p<0.05$). According to this result, passengers who recommend air travel are 16.93% more likely to perceive cabin staff service than passengers who do not recommend air travel. The third finding of the table indicates that the food & beverages (β:0.257, $p<0.05$) significantly affect the airline's recommendation. A positive β value indicates that the food & beverages variable increases the likelihood of a passenger's recommendation. According to this result, the passengers who recommend air travel are 12.93% more likely to perceive food quality than passengers who do not recommend air travel. The fourth finding states ground service significantly and positively affects passengers' recommendations (β:0.662, $p<0.05$). A positive β value means that ground service increases the likelihood of a passenger's recommendation. Passengers who recommend air travel have a positive effect on ground service. The probability of perception of service is 19.38% higher than that of passengers who do not recommend air travel. The last finding of the table indicates that value for money has a significant and positive effect on passengers' recommendation (β:1.355, $p<0.05$). According to this result, the probability of perception of value for money for passengers who recommend is 38.75% higher than that of passengers who do not recommend.

4.2. Multiple Regression Analysis for Rating Score

Second hypothesis testing employs multiple regression analysis in the second stage of methodology. Multiple regression analysis measures the effect of more than one independent variable on a dependent variable. The dependent variable in the study refers to rating scores (1 to 10) and independent variables refer to seat comfort, cabin staff service, food & beverages, inflight entertainment, wifi & connectivity, ground service and value for money variables.

Since multiple regression analysis required normality, skewness and kurtosis values are examined in Table 10. Some researchers assume that the data have a normal distribution when the value obtained by dividing the skewness and kurtosis values by their standard error is below 3.2 (Tabachnick & Fidell, 2007). According to this assumption, it is determined that the skewness and kurtosis values of the variables indicate normal distribution.

Table 10. Normality test results

Variables	Minimum	Maximum	Mean	Std. Deviation	Skewness	Kurtosis	VIF
Seat Comfort	1	5	2.46	1.377	.416	-1.138	0.778
Cabin Staff Service	1	5	2.84	1.569	.120	-1.518	0.950
Food & Beverages	1	5	2.32	1.390	.598	-.995	0.950
Inflight Entertainment	1	5	2.25	1.253	.621	-.727	0.794
Wifi & Connectivity	1	5	2.36	1.234	.525	-.702	0,.902
Ground Service	1	5	2.45	1.565	.495	-1.349	0.689
Value for Money	1	5	2.63	1.616	.369	-1.484	0.832

Following the normality test, the multiple regression analysis results are presented in Table 11.

Table 11. Multiple regression analysis results

Dependent Variable	Independent Variable	B	Std. Error	β	t	p
Overall Rating	Seat Comfort	.123	.010	.104	11.891	.000
	Cabin Staff service	.132	.009	.127	14.095	.000
	Food & Beverages	.117	.010	.099	11.373	.000
	Inflight Entertainment	.020	.009	.016	2.182	.029
	Wifi & Connection	-.004	.009	-.003	-.439	.661
	Ground Service	.253	.009	.243	27.634	.000
	Value for Money	.448	.010	.444	44.799	.000
Adjusted R^2= 0.845	Estimated Standard Error =0.642	Anova (p)= 0.000	F= 4414.235	R^2= 0.845		

Table 11 presents that 84.5% of variance in the dependent variable (rating scores) can be explained by independent variables (seat comfort, cabin staff service, food & beverages, inflight entertainment, wifi & connection, ground service and value for money). Therefore, H_2 hypothesis is supported. The individual variable relationships assessment leads to following conclusions:

- Seat comfort, cabin staff service, inflight entertainment, ground service and value for money variables affect rating scores statistically significantly ($p<0.05$). While wifi&connection variable has a non-significant relationship with the rating score.
- The increase of one unit standard deviation in independent variables affect rating score with following levels: seat comfort 10.4%, cabin staff service 12.7%, food & beverages 9.9%, inflight entertainment 1.6%, ground service 24.3% and value for money 44.4%.
- The highest impact belongs to value for money variable and it is followed by ground service, cabin staff service, seat comfort, food & beverages. The lowest impact belongs to inflight entertainment.

4.3. Anova Tests for Travel Type And Travel Class

Following the regression analysis focusing on causal relationship, the difference tests for travel type and travel classes regarding the rating score and recommendation status are employed. Tables 12 and 13 show ANOVA test results for rating scores, while Tables 14 and 15 present the ANOVA test results for recommendation status.

Table 12. Anova test results for rating scores differences in travel type groups

Variable	Variance Source	Sum of Squares	df	Mean Square	F	Sig.
Rating Scores	Between Groups	383.441	3	127.814	10.844	.000
	Within Groups	66808.212	5668	11.787		
(I) Travel Type	**(J) Travel Type**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	**95% Confidence Interval**
					Lower Bound	**Upper Bound**
Solo Leisure	Couple Leisure	.337*	.114	.017	.04	.63
	Family Leisure	.243	.123	.197	-.07	.56
	Business	.851*	.152	.000	.46	1.24
Couple Leisure	Solo Leisure	-.337*	.114	.017	-.63	-.04
	Family Leisure	-.095	.124	.871	-.41	.22
	Business	.514*	.153	.004	.12	.91
Family Leisure	Solo Leisure	-.243	.123	.197	-.56	.07
	Couple Leisure	.095	.124	.871	-.22	.41
	Business	.609*	.159	.001	.20	1.02
Business	Solo Leisure	-.851*	.152	.000	-1.24	-.46
	Couple Leisure	-.514*	.153	.004	-.91	-.12
	Family Leisure	-.609*	.159	.001	-1.02	-.20

Table 12 indicates that airline passengers' travel rating scores differ between travel types statistically significantly ($p<0.05$), therefore H_3 hypothesis is supported. The following conclusions are confirmed by Table 12:

- There is a significant difference between solo leisure type and couple leisure types in rating scores and solo leisure type passengers' rates higher than couple leisure type passengers.
- Solo leisure and business type users significantly differ in rating scores, and solo leisure type passengers' rate higher than business type passengers.
- There is a significant difference between couple leisure and business types in rating scores, while the couple leisure passengers' rate higher than business type passengers.
- Family leisure type passengers and business type passengers have significant differences in rating scores. Family leisure type passengers' rate is higher than business type passengers.

Table 13 examines the rating score with travel classes (seat types) and concludes significant differences ($p < 0.05$) between travel classes that confirm the support of H_4 hypothesis.

Table 13. Anova test results for rating scores differences in travel class groups

Variable	Variance Source	Sum of Squares	df	Mean Square	F	Sig.
Rating Scores	Between Groups	428.486	3	142.829	12.126	.000
	Within Groups	66763.167	5668	11.779		
(I) Travel Class	**(J) Travel Class**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	**95% Confidence Interval**
					Lower Bound	**Upper Bound**
First Class	Economy Class	1.494	.953	.397	-.96	3.94
	Business Class	.126	.985	.999	-2.41	2.66
	Premium Economy	.804	.985	.847	-1.73	3.34
Economy Class	First Class	-1.494	.953	.397	-3.94	.96
	Business Class	-1.368*	.259	.000	-2.03	-.70
	Premium Economy	-.690*	.259	.039	-1.36	-.02
Business Class	First Class	-.126	.985	.999	-2.66	2.41
	Economy Class	1.368*	.259	.000	.70	2.03
	Premium Economy	.677	.360	.237	-.25	1.60
Premium Economy	First Class	-.804	.985	.847	-3.34	1.73
	Economy Class	.690*	.259	.039	.02	1.36
	Business Class	-.677	.360	.237	-1.60	.25

Table 13 indicates the significant difference between business class and economy class passengers, while the business class passengers' rate is higher than economy class passengers. It is also concluded that, there is a significant difference between premium economy class and economy class passengers as the premium economy class passengers have higher rating scores than economy class passengers.

Table 14 presents ANOVA test results for recommendation status in travel type groups and concludes significant differences ($p<0.05$) between groups. Therefore, H_5 hypothesis is supported.

Table 14. Anova test results for recommendation status in travel type groups

Variable	Variance Source	Sum of Squares	df	Mean Square	F	Sig.
Recommend	Between Groups	8.229	3	2.743	11.951	.000
	Within Groups	1300.851	5668	.230		
(I) Travel Type	**(J) Travel Type**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	**95% Confidence Interval**
					Lower Bound	**Upper Bound**
Solo Leisure	Couple Leisure	.057*	.016	.002	.02	.10
	Family Leisure	.036	.017	.152	-.01	.08
	Business	.122*	.021	.000	.07	.18
Couple Leisure	Solo Leisure	-.057*	.016	.002	-.10	-.02
	Family Leisure	-.021	.017	.619	-.07	.02
	Business	.065*	.021	.013	.01	.12
Family Leisure	Solo Leisure	-.036	.017	.152	-.08	.01
	Couple Leisure	.021	.017	.619	-.02	.07
	Business	.086*	.022	.001	.03	.14
Business	Solo Leisure	-.122*	.021	.000	-.18	-.07
	Couple Leisure	-.065*	.021	.013	-.12	-.01
	Family Leisure	-.086*	.022	.001	-.14	-.03

Table 14 concludes the significant differences in recommendation status between solo and couple leisure type passengers, while solo passengers are more likely to recommend. Differences between solo leisure type and business type passengers are also included, while solo leisure type passengers tend to recommend more. The other differences take place between couple leisure passengers & business passengers' and family leisure passengers & business passengers. Both couple leisure passengers and family leisure passengers tend to recommend more than business passengers.

Table 15 concludes the significant difference ($p < 0.05$) between travel classes for recommendation variable. Therefore, H_6 hypothesis is supported. It is found that there is a significant difference between economy class passengers and business class passengers for recommendation variable. Business class passengers tend to recommend more than economy class passengers.

Table 15. Anova test results for recommendation status in travel class groups

Variable	Variance Source	Sum of Squares	df	Mean Square	F	Sig.
Recommend	Between Groups	5.056	3	1.685	7.326	.000
	Within Groups	1304.023	5668	.230		
(I) Travel Class	**(J) Travel Class**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	**95% Confidence Interval**
					Lower Bound	**Upper Bound**
First Class	Economy Class	.184	.133	.511	-.16	.53
	Business Class	.027	.138	.997	-.33	.38
	Premium Economy	.135	.138	.760	-.22	.49
Economy Class	First Class	-.184	.133	.511	-.53	.16
	Business Class	-.157*	.036	.000	-.25	-.06
	Premium Economy	-.049	.036	.532	-.14	.04
Business Class	First Class	-.027	.138	.997	-.38	.33
	Economy Class	.157*	.036	.000	.06	.25
	Premium Economy	.108	.050	.141	-.02	.24
Premium Economy	First Class	-.135	.138	.760	-.49	.22
	Economy Class	.049	.036	.532	-.04	.14
	Business Class	-.108	.050	.141	-.24	.02

5. Conclusion

The study focuses on the LCC airlines customers eWOM behavior by examining the user reviews on airlinequality.com data and employs logistic regression, linear regression and difference test methodologies to evaluate the context. Evaluating airline reviews data on Skytrax / airlinequality.com for airline research is studied in several contexts in the current literature (Lucini et al., 2020; Song et al., 2020; Farzadnia & Vanani, 2022; Wang et al., 2023b). This study extends the literature to LCC airline companies with a specific context approach.

The first part of the research indicates determinants of users' recommendation expression in user reviews. Assessing the determinants in LCC cost specifically can be helpful for extension of the literature in specific LCC areas. The findings of the first part reveal that, according to the sizes of the standardized regression coefficients, the value of money variable has the most significant impact, followed by ground service, cabin staff service, seat comfort and food & beverages variables. Accordingly, it is determined that the variability on the dependent variable is explained by the independent variables considered within the scope of the study, seating comfort, personnel service, food quality, ground service and value for money, at a rate of 87.50% (Nagelkerke R^2) and 63.90% (Cox and Snell R^2), respectively, according to two different methods. This value being over 50% is considered very important, especially in social sciences (Streiner, 1994). However, the entertainment and wifi variables have a wald value below 2 and significant values. Therefore it is found that the values are not statistically significant. Non-significant impact of entertainment is confirmed in the previous literature (Ban & Kim, 2016).

The second part continues with the relationship of user review variables with the rating score (from 1 to 10) and it concludes the specific degree of effects of determinants. The most crucial factor of the rating score is concluded as value for money, followed by ground service. Value for money finding confirms the previous literature (Mutlu & Sertoğlu, 2018; Ban & Kim, 2019; Brochado et al., 2023). The findings confirm the utilitarian side of LCC airline companies, as consumers focus on the utilitarian side more than the hedonic sides such as inflight entertainment. Insignificant relationship between wifi & connectivity also confirms the utilitarian side of the consumers.

The last part of the study focuses on the same dependent variables (recommendation status and rating scores) by comparing the travel type and seat types. The last part of the analysis reveals that business travel type users and economy class passengers have the lowest values among the other groups regarding recommendation status which is consistent with LCC airline passengers' nature in terms of economical tendencies. Traveler types examination leads to the conclusion that solo leisure type of travelers have a higher tendency to rate higher and recommendation. Travel class examination concludes a novel finding that first-class users using LCC airlines tend to rate higher and recommendation. On the other side of travel class types, economy class users have the lowest rating scores and recommendation levels. Differences between the first class and the economy classes are already included in previous studies (Punel et al., 2019). In addition, the difference between travel classes is also related to expectancy/satisfaction relationship in consumer behavior research. The expectancy levels of users can affect their rating scores and recommendation statuses.

For the managerial results of the study; eWOM phenomenon is a crucial element in digital marketing in the airline marketing industry and specific contexts - the result of having distinct characteristics- can make use of eWOM for; i) a better understanding of users' experiences, ii) detecting the gaps / effective areas in the existing attributes, iii) discovering the competitive opportunities (in terms of market analysis). From this point of view, airline marketing decision-makers must examine eWOM conversations regularly and prepare improvement/solution-fixing mechanisms for eWOM conversations. Therefore, eWOM can cause consumers to have different judgments about the quality of service due to their cultural status, past experiences, people around them, and relatives. Therefore, consumers are affected by the opinions of people around them from whom they receive similar services, live in similar conditions, or have similar cultural characteristics (Ateşoğlu & Bayraktar, 2011). In addition, consumers constantly tell each other about their experiences in daily life, and today, it has become easier to get and give advice thanks to the internet. eWOM is gaining importance in terms of consumers communicating with their social circles and acquaintances as well as strangers and reaching the information they want thanks to the internet (Ezzatirad, 2014).

Although online reviews and airlinequality.com content may signal much information regarding eWOM behaviors of airline consumers, eWOM ecosystem is not limited to online reviews. Social media posts, user reviews/comments on video channels and complaint systems on the global web can be integrated for further research studies. The inclusion of additional eWOM sources can be helpful n comprehensively evaluating the customers. The second future research direction is related to the extension of methodologic approaches, as the new technological advances in methods can be helpful to academic research and make sense of digital content. Analytical approaches such as sentiment analysis, machine learning, AI-supported systems can be helpful for future research studies in LCC airline context.

Traditional methods were used in this study. In addition to this research, future researchers can perform analyses using text mining and sentiment analysis techniques. However, the data in this study is relatively small, so research can be conducted with a more significant amount of data. In addition, although there is limited study on this subject, Alanazi et al. (2024) used approximately 7500 reviews from Skytrax to explore the determinants of airport service quality and their effects on passenger recommendations. They examined various features such as terminal cleanliness, terminal seating arrangement, terminal signs, food and beverages, airport shopping, WiFi connection and airport staff. Although the basic structure of the study is similar to Alanazi et al.'s study, in this study, within the scope of the service factor of the passengers: seat comfort, cabin crew service, food and beverage service, in-flight entertainment service, WiFi and connectivity service, ground service and monetary value of the service received were evaluated. As a result, it was determined that the scores given by the airline users for seat comfort, cabin crew service, food and beverage service, in-flight entertainment service, WiFi and connectivity service, ground service and monetary value of the service received affect the user's recommendation and play an essential role in their evaluations. In particular, it was determined that the passengers who recommended airline travel were more likely to perceive cabin crew service and ground service in addition to other service factors in the study. While Maldonado (2024) emphasizes that passenger satisfaction is primarily affected by the behavior of airline personnel (being friendly, warm-hearted, etc.) regarding airline passengers' recommendations, this study examines the impact of seat comfort, cabin crew service, food and beverage service, in-flight entertainment service, wifi and connection service, ground service, and the points given by airline passengers for the monetary value of the service on the user's recommendation and it has been determined that passengers are affected by these factors in these evaluations.

In light of the findings, recommendations for airline companies and marketers are expressed below.

The recommendations for the airline company are presented below:

- Investment should be made in seat design and comfort so that passengers can be comfortable even on long flights.
- The staff's education level should be increased, customer relations skills should be developed and personalized services should be provided to passengers.
- Menu options should be expanded, quality products should be used and special dietary needs should be considered.
- Passengers should avoid boredom during the flight by offering up-to-date and diverse entertainment options.
- WiFi and connection: A reliable and fast internet connection should be provided, allowing passengers to do their work or have fun.
- Check-in, baggage delivery and other ground service processes should be accelerated and seamless.

Suggestions for marketers are presented below.

- Detailed analyses should be conducted to determine the needs and expectations of consumer passenger types and marketing campaigns specific to these segments should be created.
- Personalized offers and suggestions should be provided using consumer data.
- Effective loyalty programs should be developed and reviewed regularly to increase consumer loyalty.
- Regional marketing strategies should be developed considering passengers' expectations and preferences in different regions.

In the study, the evaluations of users in the airline sector were tested more comprehensively with a mixed method combining both quantitative and qualitative data. It focuses on the airline sector, a more specific sector than other studies and offers the opportunity to examine users' thoughts and behaviors from different perspectives. Thus, it tries to follow the most current trends in the airline sector and shed light on the literature.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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A Study on Analyzing the Level of Public Compliance with Drone Laws in Northern Cyprus

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Abstract

The undertaking that this investigation seeks to embark upon pertains to the elucidation of the extent of legal cognizance concerning the operation of drones among the populace residing in the Girne vicinity of Northern Cyprus, particularly individuals who have attained the age of 18 years or older.

By evaluating the levels of awareness within this demographic, this study aspires to furnish significant insights that may be of utility to the Civil Aviation Authority of the Turkish Republic of Northern Cyprus. It is postulated that the findings could potentially instigate modifications to prevailing regulations, while concurrently underscoring the necessity for strategies aimed at enhancing public awareness and compliance regarding drone legislation.

In conjunction with the survey instrument, the responses of 396 participants were solicited through a battery of both close-ended and open-ended inquiries that pertained to drone-related legal stipulations, individual privacy statutes, data safeguarding laws, security protocols, restricted zones, and overarching drone regulations.

The findings of this research reveal considerable deficiencies in the knowledge of specific regulatory frameworks and indicate a pronounced lack of awareness pertaining to the repercussions that may arise from violations of drone operational statutes.

The survey results indicate that a notable 69% of participants were uninformed about how to access pertinent regulatory information, thus accentuating the critical need for improved mechanisms of information dissemination. Considering these findings, there remains an exigent requirement for a thorough educational initiative aimed at informing the public of their legal obligations and the requisite protocols for the safe operation of drones.

1. Introduction

Everyone in the modern world has come across at least one news report related to “drones,” UAVs (Unmanned Aerial Vehicles), UAS (Unmanned Aircraft Systems), RPAS (Remotely Piloted Aircraft Systems) (Keilman, 2019). Some may not know exactly what these terms imply, as they have become commonplace. With the dramatic rise in the development and use of small drones, commonly referred to as “drones” and “UAVs,” European nations and an increasing number of states around the world have attempted to provide safety policies, laws, and regulations (Labib et al., 2021). Some industrialized nations have developed elaborate drone regulations, while for many countries, regulations still do not exist (Alamouri et al., 2021). Unique challenges emerge when drone use increases in any given region; this includes unpreparedness and a lack of public knowledge, which increases the need for future research.

Additionally, with any new technology, there are often social consequences and ethical concerns. Such was the case with the emergence of the internet and social media (Green, 2021). Drones and drone use are not exempt from the failure to foresee negative consequences; they have emerged in society and thus have become a societal issue. The first place that there is an issue with preparedness is at the public level with misperceptions (Türk, 2020).

2. Literature Review

As the use of drones increases at an exponential rate, it has become paramount for governments across the globe to set up standard rules to preventpose potential dangers caused by misuse of the technology. Unmanned Aerial Vehicles (UAVs) or drones have been used widely in commercial, recreational and government areas in recent years (Labib et al., 2021). This technological advancement has however been faced with the following issues of privacy infringement, data security and possibly threats to safety. As a result, different parts of the world and individual countries have taken actions to create rules for the use and incorporation of drones within designated airspace (Türk, 2020).

Currently, the European Union (EU) has been at the forefront of regulating the operations of drones especially through the enactment of Regulation (EU) 2019/945 known as the ‘Nano drones’ regulation and Regulation (EU) 2019/947 which outlines the ‘Specific Operations Requirements’ of the drones. These regulations offer detailed specifications on manner in which drones should be manufactured, designed and operated with the intention of reducing risk associated with these vehicles (de-Miguel-Molina et al., 2018). The ICAO has also done this by issuing standards that encourage the safe operation of Remotely Piloted Aircraft Systems (RPAS) in international aviation, which are expected to be fully introduced by November 2026 (ICAO, 2024).

However, there remains significant variation as to how these regulations are applied across countries or regions. Still, some countries have managed to implement advanced regulatory environments, while others lack sufficient economic capital and regulatory framework at all (Konert & Dunin, 2020). This disparity does not only create complexities regarding the international usage of drones but also the application of safety and security policies especially in areas that have weaker regulatory frameworks (Scheppele et al., 2020).

Developing the public’s understanding and knowledge about the applicable rules and maximum surveillance and operational limits of drones is very important for enhancing compliance and safety of such operations. The findings show that over fifty percent of drone users possess a limited understanding of the prevailing rules and may inadvertently breach the guidelines, contributing to the elevation of safety threats (Green, 2021). These views were confirmed by data regarding the specific knowledge of regulatory rules, such as the distance to avoid restricted zones and privacy rights, when flying a drone; when the study was conducted in Northern Cyprus, the results showed moderate knowledge of general safety rules but relatively poor knowledge of rules and penalties (Keilman, 2019).

This is key to closing the awareness gap so that the regulations are effectively disseminated. Community programs, available on the Internet, of enforcement of present regulations for the use of drones have been proposed as feasible ways to improve understanding and adherence of drone safety matters (Lee et al., 2022). Of equal importance is the availability of current and concise information from official regulatory authorities to enhance compliance by drone users (Rushiti et al., 2024).

Based on the findings that have been identified above concerning the lack of adequate knowledge on drone usage and regulation, several recommendations are made as follows. However, educational programmes should first be tailored, to create awareness of the general rules and regulations regarding the use of drones. Such could be online training programs, public education and sensitization, incorporating drone safety, and regulation information into university and college academic programs (Mohsan et al., 2023).

Moreover, the regulatory bodies should work to ensure that they make information easily available by designing their websites and the other materials that they post in simple ways that will allow the end-users to easily find out what the current regulations are and what is expected of them in terms of compliance. Sharing such information with community-based organizations and local authorities can also help boost awareness and knowledge (McLachlan et al., 2022). Thus, it is crucial for different regulatory authorities to employ all those mentioned strategies to improve compliance and, thus, increase the level of public safety and private individuals’ privacy.

3. Regulatory Developments

In regulating the operation of civil drones in the EU, Regulation (EU) 2019/945 of the European Parliament and the Council provided the parameters for a regulatory framework. The act complements the basic regulation (EU) 2018/1976)) and lays down the requirements for the manufacture, design and acceptance of drones and drone control components and systems (de-Miguel-Molina et al., 2018). These are the types of UAS which are intended to operate in the riskier specific categories. The non-compliance of manufacturers with their regulations shall lead to withdrawal of type certificates, restrictions on the place of use, or outright ban of the UAS.

While these developments are taking place in Europe, ICAO is also working to introduce regulations on the matter. Consequently, the aviation industry has entered a significant transformation process with the integration of Remotely Piloted Aircraft Systems (RPAS). In this regard, ICAO has come up with Annex 6, Part IV to provide guidance on how RPAS can be integrated into the airspace in a safe and efficient manner. This annex contains standards and recommended practices (SARPs) governing international RPAS operations, which can be considered a breakthrough in the advancement of aviation safety and effectiveness. This regulation which has been in force starting July 2024 and will be effective from 26 November 2026 outlines the general requirements for the member states of ICAO, civil aviation authorities (CAA), air navigation service provider (ANSP), and aircraft operators while outlining the process of acquiring an RPAS Operator Certificate (ROC).

Annex 6, Part IV provides the framework for safe and harmonized operations of international RPAS. It seeks to improve operational safety through the integration of RPAS into the traditional aviation structures, take advantage of the opportunities offered by integration of RPAS into the civil aviation environment, increase operational efficiency and benefits from the use of RPAS in member state operations and to develop consistency amongst member states for improved globally efficiency in civil aviation-RPAS operations. System, such as increased operational efficiency and environmental advantages, and promote global aviation safety and efficiency by ensuring consistency among member states, facilitating smoother international RPAS operations (ICAO, 2024).

3.1. Key Provisions and Requirements

Drones will need to comply with the requirements of Regulation (EU) 2019/945. Such requirements are common for all Member States (MS) of the EU. Those common requirements essentially focus on the so-called ‘Manufacturer Side’ of the drone regulation, focusing on the requirements to be fulfilled by the manufacturer or their authorized representatives (de-Miguel-Molina et al., 2018). A core aspect therein is that the manufacturer needs to have a Quality Assurance System in place, ensuring that those drones are designed and produced properly, in accordance with a proper risk management process. Moreover, also Management and Control provisions are stipulated, ensuring that manufacturing and design provisions adhere to the requirements put forward in the Safety Management System. The core provision for drone regulation within those Regulations relies on the Extra-European Regulation EU 2019/945 and the Implementing Regulation EU 2020/746 (Lavallée, 2019). Requirements set common for all MS consists of operational limitations, categorization, and other issues. Importantly, those limitations are not assessed by the NAA before use but are enforced by the Manufacturer. Drones cannot be used for certain categories of operations without any other written approval. Limitations and restrictions comprise 'Simulations', Registered Drones', 'Service-provision', 'Software As A Service', 'Fleet Management', 'Short-term rentals', 'Accredited services', 'Remote Pilot Training', 'Compliance Monitoring', 'Data Collection', 'Data Management', 'Data Processing', 'Data Analysis', 'Data Storage', 'Multi-Use Operations', 'Operations Above 120m', 'Cross-Border Operations', 'Drone Design', 'Scope Change', 'Design Change', 'Maintenance', 'Repair', or depending on 'Service impact' and/or probable occurrence of Extended Contingencies (Konert & Dunin, 2020).

3.2. Implementing Regulation 2019/947

In this regard, three parameters should be determined for new proposed regulations based on the experience gathered with manned aviation regulatory frameworks: what to regulate (the regulatory "content"), at what level of governance to do it (the regulatory "process"), and how to regulate (the regulatory "approach"). To address the first aspect, the existing manned aviation regulatory frameworks could be a starting point to gather an understanding of "what" parameters have been considered to mitigate risks. Drawing on the developed conclusions, the broadest agreement was found that the minimum measurable "parameters" should encompass the type of operation, the type of UAV, and the mass of the UAV (de-Miguel-Molina et al., 2018). With regards the second aspect, the system of law of the EU Member States is decentralized. New regulations may be issued at the national level, the EU level or at both levels. Several motions in favor of broader EU regulation have been put forward since it is believed that EU-level rules would make UAVs operations easier in a cross-border context, as well as facilitating the emergence of a fully integrated single market (Pagallo & Bassi, 2020).

A rapid timeline for compliance has been proposed based on existing national laws. The proposed timeline encompasses an easing of existing blanket permissions, and a two-stage planned approach to additional requirements. During the first stage, existing systems would be made more transparent to authorities through continuous mandatory airworthiness checks and annual assessments of compliance with the initial permission. The second stage would introduce new requirements such as detailed descriptions of system capabilities, advanced pre-and post-flight procedures, hard-to-fake identification marks, and restrictions on pilot qualifications. Lastly, independent audits would check compliance with the previous requirements. Only after the satisfactory completion of an audit, the national law would grant the wider permission to operate UAVs at a higher risk level involving a medium or a great risk (McLachlan et al., 2022).

3.3. Registration System for Drone Users

According to Regulation 2019/947 on the rules and procedures for the operation of unmanned aircraft, drone users must register with the relevant authority before they can fly their drone. This regulation establishes a registration system for drone users which comes into effect from 31 December 2020 (de-Miguel-Molina et al., 2018). All drone users must apply online for registration with the relevant national competent authority. The regulation specifies the responsibilities of the Member States and the Commission regarding the registration of drone users. Member States must set up and operate a registration system for drone users, ensure they have a unique identification number and establish an electronic system to provide this identification number (Rushiti et al., 2024). The Commission must develop a user-friendly central database of drone users which holds the identification numbers and relevant information on the drone users.

Every drone user is required to register with the relevant authority as soon as they decide to use a drone or drone services (McLachlan et al., 2022). National legislations hand this task to the national authorities who are obliged to set up a registration system following specified conditions. The Commission will also take the lead in developing a central database to ensure all drone users in the European Union have a unique identification number. There are significant fees attached to the registration, which is a one-time cost incurred by all users that do not necessarily own drones. The more advanced and more capable drones that might be misused also face higher fees, but it is noteworthy that all users including toy drone users face them. The regulation also specifies timeframes however it is doubtful whether Member States can comply with these on time (Belwafi et al., 2022).

3.4. Classification of UAS Device Classes

Classification of UAS device classes is stipulated in the Implementing Regulation 2019/947. UAS device classes are classified as UAS device classes. UAS device classes can be classified under four. Class of UAS device shall be determined by the following parameters, including: the maximum mass of the UAS taken off on purpose – not exceeding 250 g, from 250 g up to 2 kg, from 2 kg up to 25 kg, and from 25 kg (Nikodem et al., 2018). The deployed geographical area of operation of the UAS on design purpose, including operation in the 'Open' category, operation in 'Specific' category, and operation in the 'certification basis' category (de-Miguel-Molina et al., 2018). The operational purpose of the UAS on design purpose, including Uplink video, photographic and or other sensory data capture, UAS freight transport, UAS operation for Surveillance and monitoring of activities and events, and UAS operation to provide telecommunication networks.

Once class of UAS device is determined, and the parameters envelope pertinent for compliance demonstration purpose is defined, the operational requirements of the UAS device including limitations and restrictions shall be specified as per Chapters 3 to 8 of the new article. The classification of UAS device classes is only applicable to UAS devices that are not specifically in the declared drone market, to quote the respective brand and models selling UAS devices in the market, but to clarify, ownership of such UAS devices does not exempt compliance to the technical requirement stated in the new regulatory framework.

3.5. Variations in Implementation Among EU Member States

In January 2018, the European Authorities established an aviation safety agency in charge of the regulation and safety oversight of drone operations. Following this resolution, the TRNC also evaluated its situation towards the regulations of drone applications and initiated efforts to prepare regulations (de-Miguel-Molina et al., 2018). The EU common safety rules began to be applied by the member states in July 2020. The regulation of drone applications is presented as a narrative comparison between the EU member states (Scheppele et al., 2020). In the first chapter, necessary background information is provided about the EU and its member countries. There is general information in the second chapter about drone applications in the world and their benefits and risks. In the final third chapter, there is a discussion of the regulatory requirements in the EU and its member states, and the intended regulation approach in the TRNC. It is observed that the already accepted drone regulations by the EU member countries are quite different from one another. This is an obstacle for the free circulation of drones among EU member states. On the other hand, similar problems with many EU countries are also being faced in the TRNC.

In studies conducted since the 1990s, the use awareness of drone applications in EU member states has been evaluated, and their efforts to prepare regulations have been scrutinized. By means of an online survey, drones' usage in urban settings, public awareness, possible advantages, and concerns of citizens about drone applications have been investigated. Analyses of evaluations and efforts to prepare drone regulations in EU member countries have indicated that, while some member states possess intensive usage and investments in drones, some other states have low to nonexistence awareness of drones (Lavallée, 2019). With all these efforts, it is indicated that the authorized agencies of the states located in central EU countries are more active in the preparation of regulations. On the other hand, the need for regulation is reported by almost all EU member states.

National regulations relating to drone flying generally include:

- Registration of the drone, drone operator, and/or pilot.
- Possession of a drone liability insurance policy (may include EU standard).
- Compliance with technical and airworthiness requirements outside EU rules.
- Certification and/or approval of the drone outside EU rules.
- Safety zones where no drone flying is permitted outside EU rules.
- Local restrictions on drone flying outside EU rules.
- Limitations on the use of drones for commercial purposes/specific applications outside EU rules.
- Additional drone pilot training requirements outside EU rules.
- Compliance with a national drone flying code of conduct (may include EU standard) or other provisions outside EU rules (Thompson et al., 2024).

3.6. Challenges in Enforcement and Compliance

Creating a regulatory framework for the operation of UAVs poses significant challenges in enforcing compliance. The fine line separating those who obey the regulations from those who do not becomes increasingly difficult to enforce. As these machines become cheaper and increase in numbers, there could be a tendency for failure to comply with airspace regulations. In this regard, UAVs over the top of high-security areas may play the role of a fly-on-the-wall, shooting photographs or video-feeding in real time and endangering civil liberties. UAVs mean easier infiltration into airspace and a big challenge to the current airspace security paradigm (Mohsan et al., 2023)

Even without the legislation of drones and UAVs, defense in depth would be an important priority, especially in the case of determining the combat zone. Combat identification of a drone using its on-board sensors operating in the tactical frequency bands would be easy for operators on the non-combat side of the combat zone, most of which would be friendly in the airspace over military maneuvers (Di et al.2021). All radars whose antenna does not point at the UAV approaching on a ground clock angle would be ineffectual until the drone passes the airspace, anything between a minute to a month in advance depending on the advance over ground tactical speed, while easily feasible jamming of the drone on its path to the combat zone would hardly affect the targets on that same side. Once in the airspace over military operations, either redundancy in air defense radar is required or legislative changes to grant access to defense contractors' intelligence drones and information they can relay to their clients' government, neither of which seems too probable (Rossiter & Cannon, 2022).

Similarly, the infiltration of drones of non-friendly governments and armed non-state organizations on a covert path is a possibility and may have already occurred. Military-grade drones, for instance, can be disassembled and sent through a series of camouflaged shipments, preferably without a sign of consistency for them not to be suspiciously analyzed, and a routine period of delivery which might make it impossible to reconstruct them before the premeditated operation. They may even fly under the cover of a commercial UAV company hired to do prospecting or studying the physical features of an area of interest, but who are in fact just gathering intelligence and observing the air defense capabilities appreciably on a random time of the year to set up a low-risk target, with later installments of flights controlled by a likely projectable future scenario.

4. Drone Regulation in TRNC

There are several issues directly impacting privacy, safety, disruption, noise, terrorist attacks, malicious use, or matter conflict by drones that need to be curbed or controlled by the government, while there are significant advantages, innovation, and increment in daily comfort, safety, speed, effectiveness, etc. that compel the additional growth of drone technology and operations (Lee et al., 2022). In the TRNC, the use of drones is regulated by various safety and operational restrictions. These guidelines are designed to ensure the safe and responsible use of drones by setting specific weight limits and permission procedures.

Imposing stringent restrictions regarding the use of drones in the TRNC is aimed at preventing threats to airspace and preserving security. In particular, these rules are applied to reduce possible risks in the airspace, to exclude unlawful actions in some zones, and to provide immediate actions, if necessary. Such regulations ensure that drone technology is used in a safe and prudent manner while setting the standards that must be adhered to in terms of operation and safety (Civil Aviation Department of TRNC).

Main restrictions and safety measures involved in the drone regulation system in the TRNC;

-Weight and Altitude Restrictions: The maximum weight allowance for UAVs to operate within TRNC airspace ranges up to only 249 grams. It is permissible to fly drones below this weight at a height of up to 50 meters above the land under some circumstances without seeking approval from the Civil Aviation Authority. Such conditions include that the operator has undertaken the required training and is not under the influence of alcohol or any other drugs.

-Visual Contact and Safety Distance: Operators should also be able to visually always monitor their drones. They are also supposed to maintain the least altitude difference of 150 meters to avoid collisions with other aircraft, people, vehicles, marine vessels, and structures. These are flights in congested airspace or over events, where approval must be sought not less than five working days before the flight.

-Prohibited Zones and Safety Areas: A security buffer is set up of 6 km around any airports and a 1. Area within a 5-kilometer radius of the helipads where UAV operations are prohibited. Moreover, no flight is allowed in sensitive areas, including prohibited areas, military facilities, populated areas, and archaeological sites without the permission of the controller. Aerial photography of military restricted areas is prohibited. However, nominated aerial photography of restricted military zones is prohibited.

-Flight Records and Reporting Obligations: The candidate shall keep a record of flight hours and other appropriate details as a logbook. These records must be maintained for at least two years and the Civil Aviation Authority must have access to these records. In addition, any occurrences or incidences concerning drones must be brought to notice within 48 hours.

-Registration Requirement: All drones used in the TRNC must be registered with the Civil Aviation Authority. This registration should include the drone's technical specifications, model and serial number, and the operator's contact information (Civil Aviation Department of TRNC).

5. Methods and Study Design

A survey focusing on information related to the regulations governing non-commercial drone usage in the Turkish Republic of Northern Cyprus was conducted by the Civil Aviation Management Program of Cyprus Science University among individuals aged 18 and over residing within the borders of Kyrenia between the dates of 02/02/2024 and 27/08/2024. The survey was carried out with a total of 396 participants, consisting of 271 men and 125 women. The sample was selected from those aged 18 and over who are legally responsible for their actions according to the laws of the TRNC. The total number of individuals aged 18 and over in the Kyrenia region was determined to be 35,397. Calculations using the sample size formula with finite population correction indicate that a sample size of approximately 381 would allow us to reliably estimate the characteristics of the population in the Kyrenia region with a 95% confidence level and a 5% margin of error (Cochran, 1977). In this study, however, a total of 396 participants were reached.

$$n = \frac{Z^2 \cdot p \cdot (1-p)}{E^2 -} \cdot \frac{N}{N + \left(\frac{Z^2 \cdot p \cdot (1-p)}{E^2} - 1\right)}$$

$$n = \frac{1.96^2 \cdot 0.5 \cdot (1-0.5)}{0.05^2} \cdot \frac{35397}{35397 + \left(\frac{1.96^2 \cdot 0.5 \cdot (1-0.5)}{0.05^2} - 1\right)}$$

$$n \approx 381$$

5.1. Evaluation of Survey Results

The aim of the study is to measure the levels of legal awareness related to drone usage and to share the findings with the TRNC Civil Aviation Authority, thereby influencing potential amendments to existing regulations and highlighting the need for adjustments that will enhance public awareness. Participants were informed in advance about the content and purpose of the survey. Since the survey was anonymous, there was no need to obtain informed consent. The participants' task was to anonymously respond to 13 closed-ended questions by selecting one of the options: 'yes,' 'no,' or 'maybe.' They could also express their general opinions through 2 additional questions. To effectively analyze the survey responses, the questions were divided into three thematic categories. The first category addressed demographic information (Q1-Q3), the second category covered experience and ownership (Q4-Q5), and the third category focused on awareness of drone regulations (Q6-Q15). However, questions 8 and 14 aimed to understand participants' true level of awareness by requesting their own views, knowledge, and comments. Based on this approach, the results have been obtained as follows.

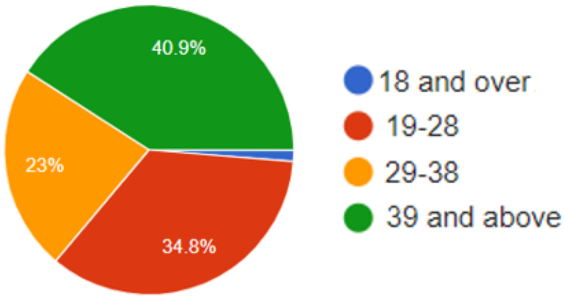

Figure 1. Age Distribution

40.9% of respondents are aged 39 and above, indicating that most survey participants are in the more mature age group. Younger age groups, such as those aged 19-28 (34.8%) and 29-38 (23%), also make up a significant portion of the participants. This age distribution provides a broad perspective in examining awareness levels about drone usage and regulations across different age groups. This situation indicates that older individuals have higher levels of awareness.

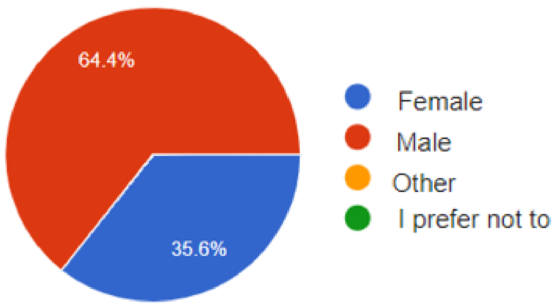

Figure 2. Gender Distribution

64.4% of respondents are male, while 35.6% are female. This gender distribution might suggest that men show more interest in drone usage and related regulations, or that they are more active in participating in such surveys.

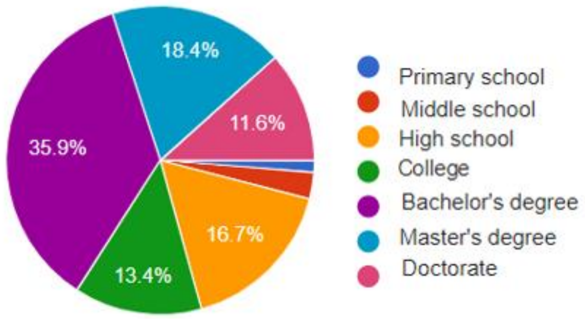

Figure 3. Educational Status

35.9% of respondents hold a bachelor's degree, 18.4% have a master's degree, and 11.6% have a doctoral degree. This high level of education indicates that the respondents are generally well-educated and potentially more aware of regulatory and technological issues.

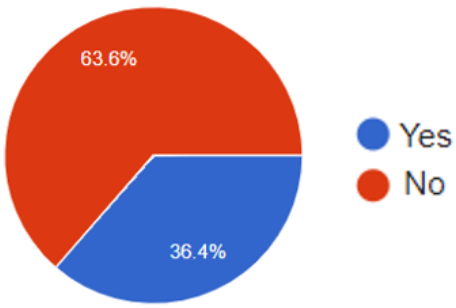

Figure 4. Experience with Drone Usage

63.6% of respondents have never operated a drone before. This indicates that drone usage is not widespread, or that most participants have not yet had the opportunity to try this technology.

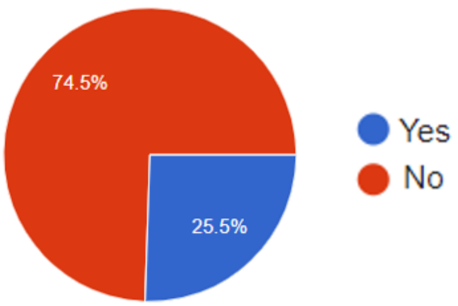

Figure 5. Drone Ownership

74.5% of respondents do not own a drone. This suggests that drone ownership is relatively low, and many people may still not consider purchasing or using this technology.

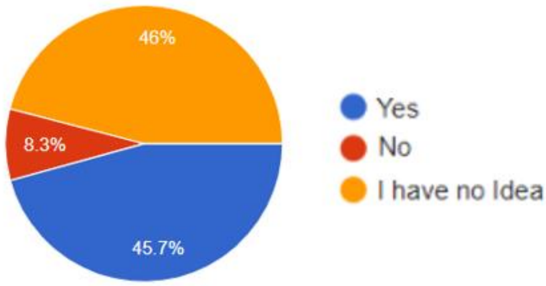

Figure 6. Awareness of Existing Drone Legislation

46% of the respondents stated that they were unaware of the existence of drone legislation on the other 45. 7% of the people know that it exists. This indicates that there is a serious vice in the promotion of drone regulations and that the users should be made to have more knowledge about these regulations.

Figure 7. Knowledge of How to Access the Regulations

69.4% of respondents said that they are not aware where they can find information on drone regulations. This means implying that these regulations in question or the ways in which such information can be obtained are not easily available to the general public.

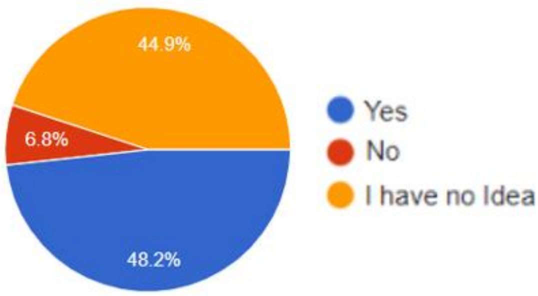

Figure 8. Registration Obligation

44.9% of respondents are unsure about the requirement for drone registration. This highlights the need for more information dissemination regarding registration requirements.

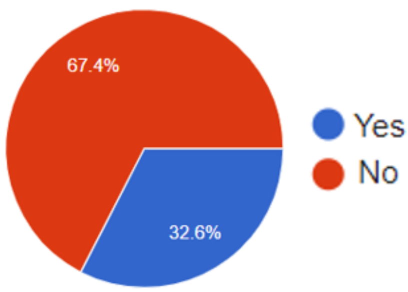

Figure 9. Awareness of Altitude Restrictions

67.4% of respondents had no idea about altitude regulations concerning drones. This implies a very poor level of safety knowledge and compliance, thus a high number of potential safety hazards.

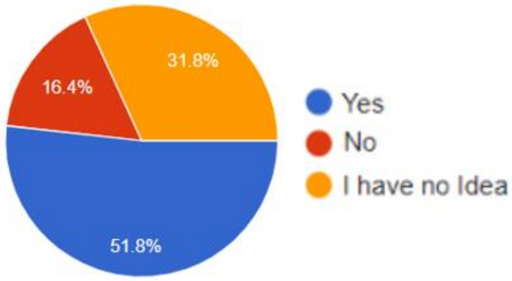

Figure 10. Knowledge of Authorization and License Requirement

51.8% of respondents believe that a license or authorization is necessary for drone operation, while 16.4% think it is not required. Additionally, 31.8% of respondents stated that they are unaware of such requirements. These results indicate a widespread lack of awareness regarding licensing requirements for drone usage. More clear communication about licensing and authorization is essential to increase compliance with the regulations.

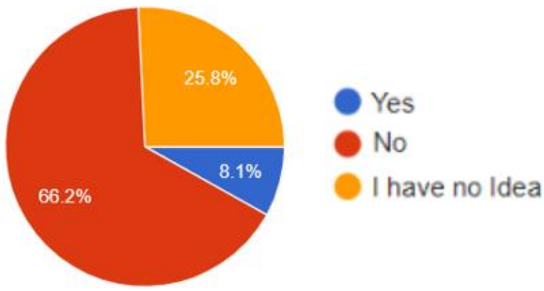

Figure 11. Operational Zone Knowledge

66.2% of respondents indicated that operating a drone near an airport is illegal, However, the fact that 25.8% of respondents are unsure about this highlights a lack of comprehensive understanding of safety rules near airports, suggesting that more information dissemination is necessary. The 8.1% who believe it is legal to operate near an airport reflect a potentially dangerous misunderstanding.

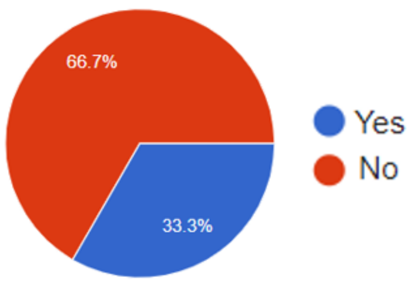

Figure 12. Awereness of the Privacy and Data Collection

66.7% of respondents indicated they are not aware of the privacy and data collection rules related to drone usage. This shows a significant gap in knowledge concerning personal data protection and privacy. Increased awareness and education could help users become more sensitive to privacy rights.

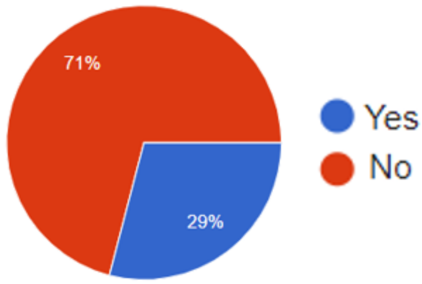

Figure 13. Awareness of Sanctions For Non-Compliance with Laws

71% of respondents are not aware of the sanctions that may be applied if a drone is not operated legally. This indicates that legal regulations are not well understood, and there is a need to raise awareness about potential sanctions. Addressing this lack of knowledge is critical to improving compliance with regulations.

Two more open-ended questions were taken from the previous study and tested along with the closed-ended questions in the survey.

To the question of where the regulations can be accessed responses show that majority of the survey participants said they directly get information regarding the legal regulations for the use of drones over the internet. The official regulatory authorities emerged as the most mentioned source, often using broad terms for them such as 'civil aviation' or 'Directorate General of Civil Aviation.' A few participants also mentioned two websites specifically and the ability to access further information via internet searches.

However, there are concerns as a significant percentage of the responses contained phrases such as 'I don't know' or similar statements, suggesting that some of the participants are not aware of the specifics of the existing regulations, or are not aware of how to obtain this information themselves. A few other participants mentioned international aviation authorities (e-g., ICAO, EASA) or local authorities, which indicates that the awareness level is not uniform among the participants.

These responses indicate that the level of awareness in the Kyrenia region, among the people aged 18 and over, regarding the ways of obtaining the regulations on drones and other information concerning these regulations is different. This situation proves that accessing information can be different and there are some problems with the awareness of the corresponding authorities. It can be pointed out that there is a need for familiarization and awareness campaigns as many participants indicated that they either do not know how to obtain this information or have inaccurate information. This could result into difficulties in following or observing the legal requirements concerning drone operations. From the responses to the open-ended question, it is evident that there is lots of awareness among participants concerning the rules regarding privacy and data collection. The majority of answers focus on prohibitions of photographing or obtaining information in military facilities, on private territories, and in places that could infringe personal privacy.

Some of the participants mentioned in particular that it is prohibited to collect information about a person, or his property without the latter's prior consent and that it is impossible to use such information when the subject does not consent to it.

One common notion that arises out of the responses is that, before taping people or invading their privacy through photography, consent must be sought. It is well understood that such operations should be kept out of the reach of the vicinity of residential buildings and people and a safe buffer should be kept ensuring that privacy is not invaded. There are cases where the participants referred to the particular legal requirements indicating an awareness of the existing legal provisions.

Furthermore, there are other comments about restricted areas like 'military sites,' 'airport,' or 'historic regions' to suggest participants' understanding of security issues and security measures under national security laws. This consciousness of regulation can also be inferred from the acknowledgement that permissions from the respective authorities are necessary before flying drones in certain zones. Although some of the answers suggest a specific regulation or procedure that the participant was unfamiliar with or only partially aware of. This means that although the public appreciates the value of privacy and protection of their data, they may lack adequate knowledge of the specifics of these regulations across the different fields.

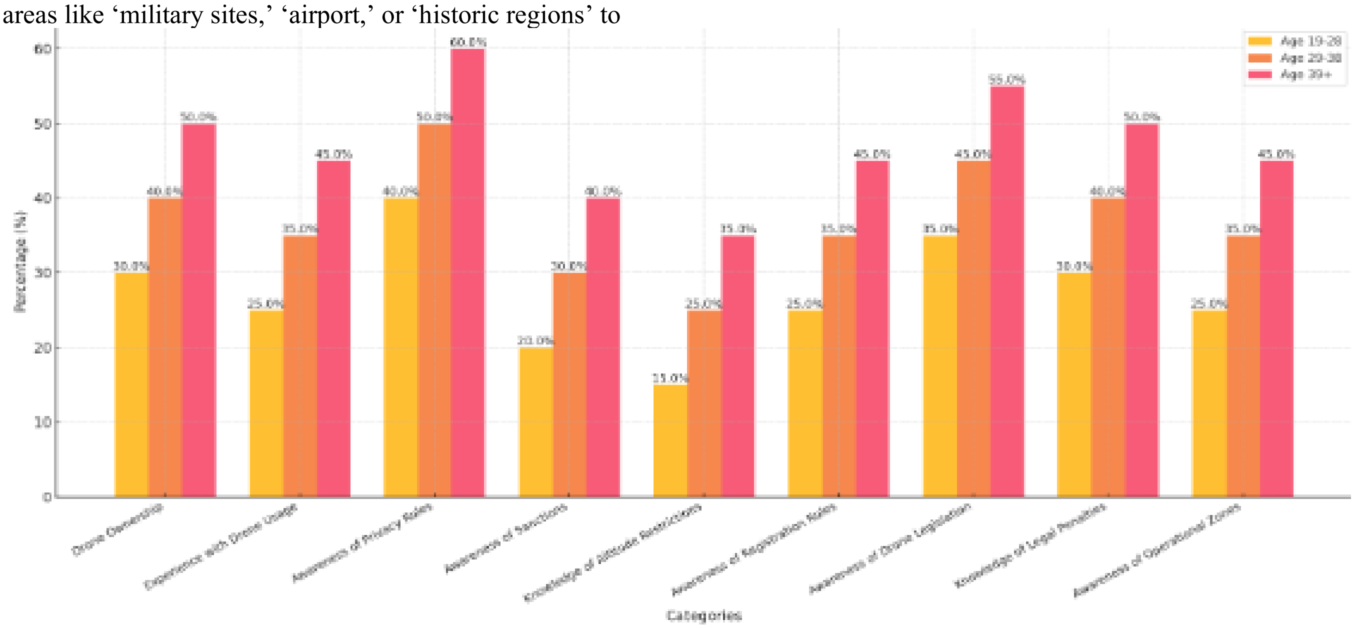

Figure 14. Comparision Of Awareness Level By Age Group

The data on the correlation of age brackets with various categories of awareness demonstrates a very striking pattern: the awareness about the level of knowledge concerning operational zones, legal aspects, and privacy dos and don'ts increases steadily with age. Therefore, it stands to reason that, compared to the younger population, older people aged 39 and above have a better grasp of drone-related concepts.

One answer to this paradigm might be the social cognizance built up due to the lifetime experience and responsibilities of older people where appreciation of regulatory laws may be more pronounced. For example, the people who belong to the 39 and older category are likely to already be or for a long time will be engaged in professional or leisure activities where they will have to know how to own a drone, operate it, and also know the laws regulating it. Also, older respondents understand better privacy and safety issues, hence the higher knowledge they had about privacy prohibitions and penalties.

On the other hand, younger people (ages 19-28 and 29-38) show lower levels of awareness, especially when it comes to technical and legal rules about drones. This might be because they haven't been exposed to or aren't very interested in drone regulations, as they likely use drones more for fun or casual purposes. Also, their lower awareness could mean there's a lack of education or information designed specifically for younger people.

From a policy standpoint, these results show the need for focused education efforts to help younger age groups understand drone rules better. Adding drone regulations to school programs or using social media and other online platforms that younger people use could help improve compliance and safety when using drones. At the same time, since older individuals are more aware of these rules, they could play an important role in encouraging safe and responsible drone use in their communities.

In short, this study highlights the importance of tailoring awareness campaigns to fit the unique traits and requirements of different age groups. By focusing on these differences, regulators and educators can better share information about drone rules and safe practices, making their efforts more thorough and impactful.

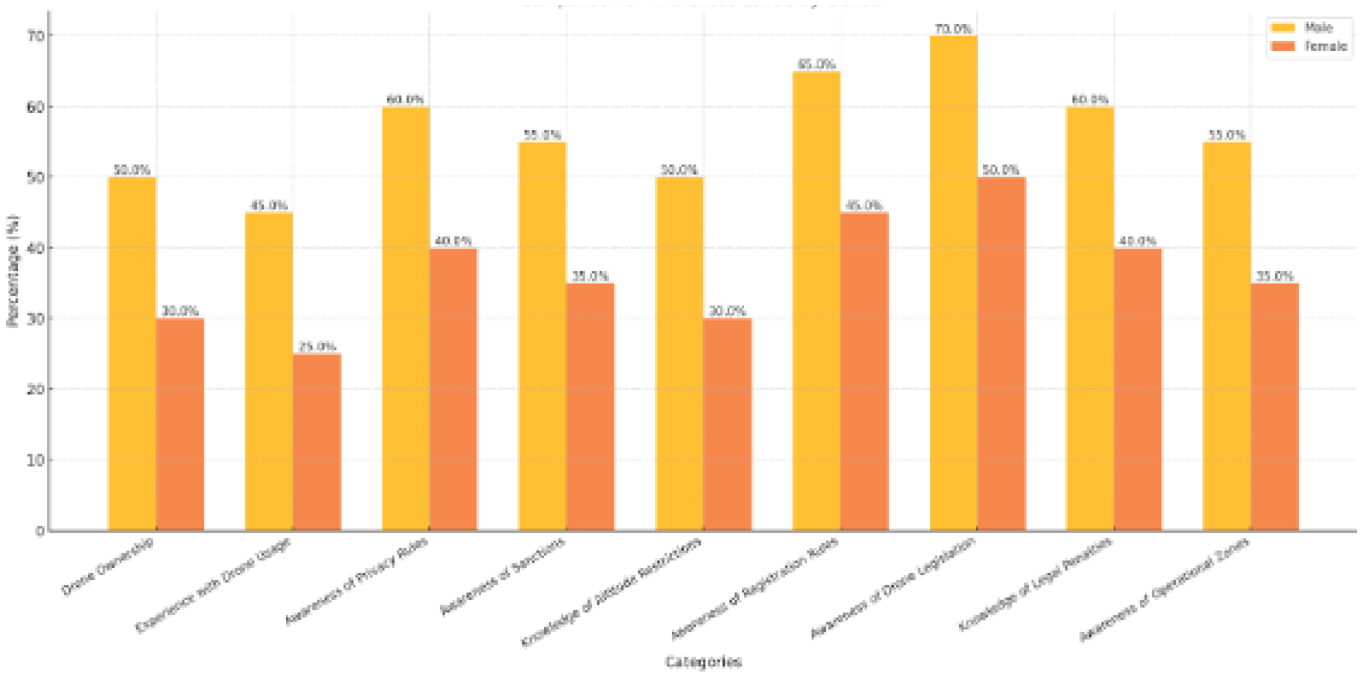

Figure 15. Comparision Of Awareness Level By Gender

The differences in how men and women understand and are aware of drones can be explained by a few reasons. Men might have more chances to use drones, either for work or hobbies, which makes them more familiar with how drones work and the rules around them. On the other hand, women might not have as many opportunities to use drones, possibly because of societal norms or fewer chances to engage with technology. Men might also see drones and their rules as more important or useful in their daily lives or jobs, so they pay more attention and learn more about them. Women, however, might not feel the same connection or relevance to these topics.

These differences could also point to problems in how information about drones is shared. If the materials or campaigns about drones and their rules don't consider both men and women equally, women might not get the same level of information. Also, traditional ideas about gender roles and what society expects from men and women might affect how they interact with drones and related topics.

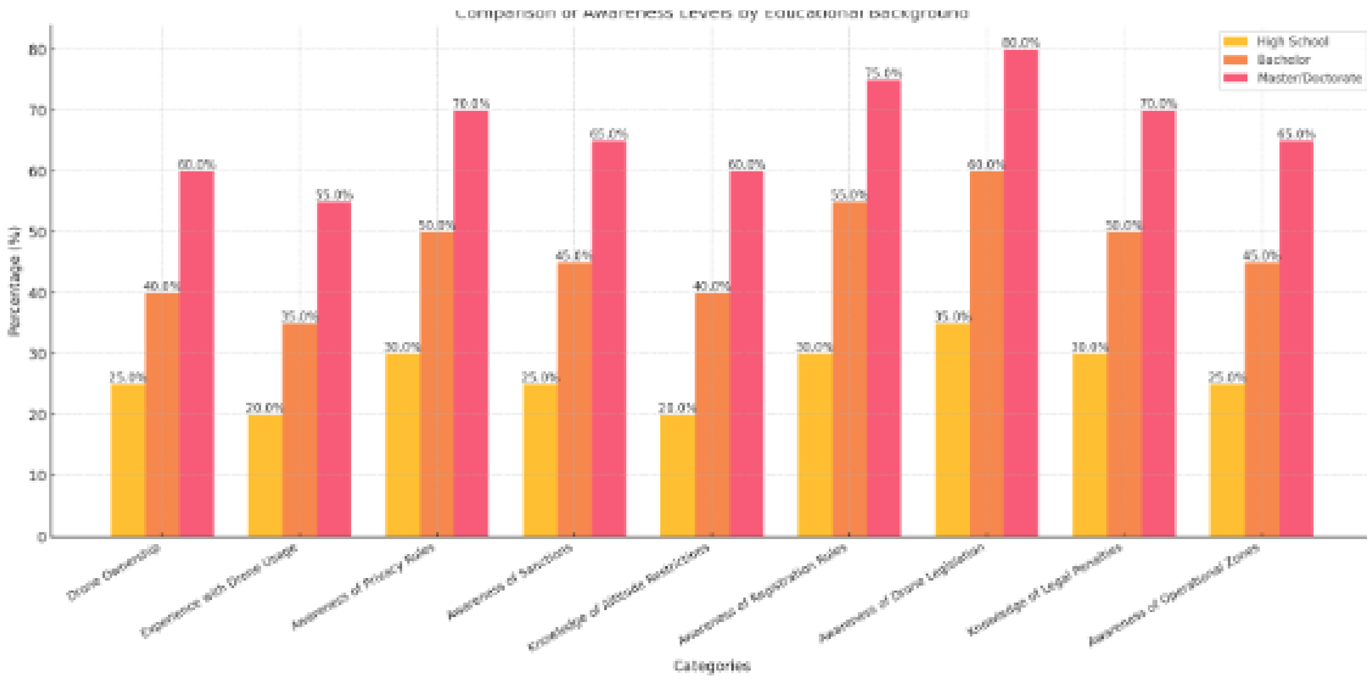

Figure 16. Comparision Of Awareness Level By Educational Background

The chart shows a clear link between education and how much people know about drones. People with more education, especially those with Master's or Doctorate degrees, know more about owning drones, how to use them, and the rules for flying them. In contrast, people with less education, like high school graduates, know less about these things.

Going to college or university probably gives people better access to resources, teaches them how to do research, and lets them use advanced technology. All of these things help them become more aware of important issues. For instance, people with higher degrees show the most awareness in areas like knowing the legal consequences of breaking rules (70%) and understanding drone laws (80%). This suggests that formal education might be very important in helping people understand complicated topics, like the legal and ethical issues related to using drones. On the other hand, people who have finished high school show much less awareness in all areas, such as owning drones (25%) and knowing how to use them (20%). This difference points to a possible issue in how education and information are shared, especially for those with less formal education. It indicates that the current efforts to educate and inform might not be doing enough to help this group.

The findings from the survey of respondents from the Kyrenia region are crucial in establishing public knowledge on the legality of non-commercial drones. The results indicate that while, participants show average of average levels of general knowledge, fine-tuned to regulation such as privacy protection and no-go areas as the military no entry zones, private property, etc. there is a major lack of awareness about specific regulatory observations and the penalties accompanying violations to them. In this respect, the lack of broader legal literacy is truly reflected in the lack of educational programs and better methods of distribution.

The survey results, therefore, show that a large number of the respondents were not sure on how to get pertinent information from the regulators, which can be inferred to mean that the current efforts at dully communicating with the regulators are ineffective. It is crucial to address this issue to ensure that there is a high level of safety and compliance with the regulations by the users of drones. Timely and clear updates on rules and regulations concerning the usage of drones should be provided to the public adequately and comprehensively.

Further studies should include comparative cross-sectional studies encompassing a higher participation of the general population to build a wider picture of the populace's awareness. These studies could help create specific information and educational materials and Internet-based training modules easily incorporated into educational programmes, or integrated into media campaigns, to enhance legislative knowledge in the field of unmanned aviation.

The aforementioned gaps in knowledge and dearth of awareness could help increase compliance with drone-related legal requirements as established by the TRNC Civil Aviation Authority and other regulating agencies and foster public safety and the privacy of the individual. Stakeholder involvement via focused discussion and partnership will be valuable in the proper execution and further evolution of drone rules.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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An Examination of Serious Runway Incursion Incidents Resulting from Air Traffic Control Services

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Abstract

With the development of aviation transportation in the world, the number of aircraft accidents has also increased numerically. Although as a result of technological advances the equipment and reliability of aircraft have increased technically, errors and violations caused by human factors involving air traffic controllers and pilots as the main actors of aviation, continue to exist as serious causes of accidents. When serious aviation incidents resulting from the execution of air traffic control services are examined, factors such as lack of communication, lack of teamwork, lack of positive safety culture, organizational functioning, stress/chronic fatigue, situational awareness and inadequate supervision appear to be of serious importance in causing accidents/incidents. The study aims to determine the factors that are likely to cause accidents/ incidents by examining the serious aviation incidents caused by air traffic that occurred and recorded in the world between 2012 and 2022, and to offer suggestions to reduce risks to an acceptable level by taking precautions before accidents/ incidents occur in accordance with a proactive approach.

1. Introduction

It is possible to describe the concept of safety which is encountered wherever humans are present as the state of being free from danger resulting from natural forces or human error (Nas, 2015). ICAO (International Civil Aviation Organization) describes safety in terms of air traffic control services as the state where risks related to aviation activities are reduced and controlled by decreasing them to an acceptable level, and the main purpose of safety culture is described as reducing the unsafe behaviors of the workers to an acceptable level by the support of the management (ICAO, 2016).

There is always the potential of making mistakes if there is human involvement; therefore, it is inevitable to have the of safety policies in order to minimize the errors. The concept of safety is always important for reducing errors in every sector, however; since the scale of the danger and human related risks can lead more severe consequences, it becomes more crucial in some sectors. Aviation sector is among the leading sectors where human errors can cause serious consequences. ICAO has stated that human factor has a steadily increasing effect on the occurrence of unsafe incidents in aviation (ICAO, 2018).

Along with developing technological possibilities, human related factors have substituted technological causes in factors leading accidents and incidents, the examination of the place of air traffic controllers in human factors has become more significant.

The importance of safety in air traffic services has made it necessary to establish a safety system for air traffic controllers Even though all the precautions are tried to be provided in order to eliminate risks, it is not completely possible to purify a system, where there is 'human', from danger and operational errors. What is essential is that to control the risks in the system and maintain them in a reasonable level by managing them. A system with reasonable level risks is accepted as 'safe' (SHGM, 2022).

It is known that a lot of undesirable incidents happening in aviation sector is directly and indirectly related to human factors. Considering the significance of human factor in unsafe incidents, a close examination of human factors is critically important for pilots and air traffic controllers, who play the most significant roles within the aviation community related to aircraft operations (Moon et al., 2011).

In this study, runway incursions in air traffic control services which lead serious aviation incidents resulting from human factor are going to be discussed. A runway incursions occur when an aircraft, ground vehicle or a person enters a runway or runways. Runway incursions are incidents that are very difficult or dependent to luck to resolve for the cabin crew or the pilot of an aircraft that is in motion on the ground or landing.

2. Materials and Methods

The main purpose of the study is to determine factors that cause undesirable serious incidents in aviation, to prevent risk factors that lead the occurrence of accidents/incidents before they even occur as required to proactive approach or to reduce risks to an acceptable level.

In this study, content analysis as one of the qualitative research techniques is employed in order to determine factors that can lead severe aviation incidents. Content research is a research approach that meticulously analyze, study and verify the contents of written data (Cohen et al., 2002).

In compliance with the purpose of the study, serious incidents that occurred worldwide between 2012 and 2022 and whose reports were prepared by aviation authorities of related countries and that cause runway incursions have been analyzed. A total of 225 serious incidents related to runway incursions were encountered over the span of this decade in the world and among these incidents, incidents whose final reports were drawn by relevant civil aviation authorities were collected, similar incidents were eliminated and a total of 16 serious incidents were analyzed. Relevant serious aviation incidents were compiled by comprehensively examining web sites of aviation authorities of the respective countries, sector reports on air traffic control service deficiencies and relevant scientific articles about the incidents.

In the study, content analysis was conducted on 16 serious incidents, examining seven factors. These are organizational functioning and unsafe supervision, as the components of the Human Factors Analysis and Classification System (HFACS), teamwork, situational awareness, stress and chronic fatigue, communication as the components of Team Resource Management (TRM) and positive safety culture as the component of safety culture. These 16 incidents are about the incidents on runway incursions. Since there is no chance to utilize developed technologies such as ACAS X/TCAS (Airborne collision avoidance system/Traffic alert and collision avoidance system) systems that step in as a result of hazardous aircraft proximity and warn pilots, CWP (Controller working position) that effectively generates alerts in situations which require the controller to be aware of dangerous aircraft proximity and STCA (Short term conflict alert), MSAW (Minumum safe altitude warning), APW (Area proximity warning) and APM (Approach path monitor) that are safety nets, human factor in those incidents are at its highest level. While human errors are minimized through systems in other air traffic control services such as approach and area control services, human intervention is essential in runway incursions within the airport control services. When examining accidents and serious incidents based on the phase of flight between 2012 and 2022, it is observed that 70% of the incidents occurred during aircraft approaches/landings, pushbacks, taxiing on the runway, and takeoffs (EASA, 2023).

When aviation incidents occurred between 2012-2022 are evaluated in terms of accidents/incidents and serious incidents, 68% of 366 serious incidents occurred in Eurocontrol region between 2012-2017 were the incidents on runway. When accident/incidents occurred again in Eurocontrol region between 2018-2022 are evaluated, 52 of 122 experienced incidents constitute the incidents occurred in runway. Accidents related to undesirable incidents after runway incursions or incidents occurring after runway excursions or touchdown accounted for 29% of the accidents in which aircraft sustained significant damage in 2020 worldwide (EASA, 2019, EASA, 2023, ICAO, 2021).

In 2020, 66% of serious incidents involving aircraft over 5700 kg occurred due to abnormal runway contact (ARC) and touchdown of landing gears, runway incursions (RI) or runway excursion (RE) and turbulance (TURB) of the plane. Additionally, again in the same year, 75% of aircraft accidents resulting in serious injuries were caused by runway incursions or runway excursions (RI/RE). In serious incidents, the primary cause of aircraft damage was again due to abnormal runway and touchdown contact conditions (ARC), runway incursions (RI), or runway excursions (RE), accounting for 61% of the cases (ICAO, 2021).

Meanwhile, a total of 3103 incidents were reported in Turkey in 2022. 107 of these incidents includde conditions due aerodrome (ADMR), 135 of them were due to incidents in ground handling (RAMP), 127 of them included incidents that were related to runway and runway connection conditions due to abnormal runway and touchdown of landing gears (ARC). Moreover, 1092 of these incidents occurred due to strikes or near strikes with animals such as bird and/or wild animals (BIRD) at ant stage of the flight. Incidents related to runway incursions accounted for 47% of all reported incidents in Turkey in 2022 (SGHM, 2022).

In the study, 225 runway incursions that occurred between 2012-2022 in the world and recorded by being investigated in detail by the aviation authorities of relevant countries were analyzed (Skybrary, 2024). 40 of the analyzed runway incursions were determined as incidents with a potential to cause serious accidents in case of not being prevented at short notice. Of the 40 serious incidents, 16 were examined in detail after filtering out those with similar error factors that caused the incidents.

2.1. An Analysis of Serious Incidents Caused by Air Traffic Control

It is possible to categorize serious incidents caused by air traffic control as vertical and horizontal proximity, runway incursion and excursions of aircraft. In the analysis of serious incidents parts of the study, serious incidents resulting from runway incursions were analyzed since the controllers closely affect the intersectoral interactions. While examining runway incursions which could have resulted in disaster if not prevented at the last moment, in-depth analysis was conducted on the incident contents which were recorded by the aviation authorities of the respective countries and used as educational documents.

2.1.1. Incident 1

The incident occurred on April 27, 2021, when a Boeing 737-400 of TNT Airways (call sign TAY4959), operating a scheduled international cargo flight from Porto airport, noticed a vehicle on the runway just ahead during takeoff under night conditions with good visibility. As soon as TAY4959 sees the vehicle, it took off with a rotation maneuver and at 490 feet above the location of the vehicle, the vehicle was moved to the side of the runway with the instructions of the controller. On the day of the incident, the controller worked for 4 hours continuously without having a break by managing on all the other sectors that are connected to the control tower on a single frequency (GPIA, 2021).

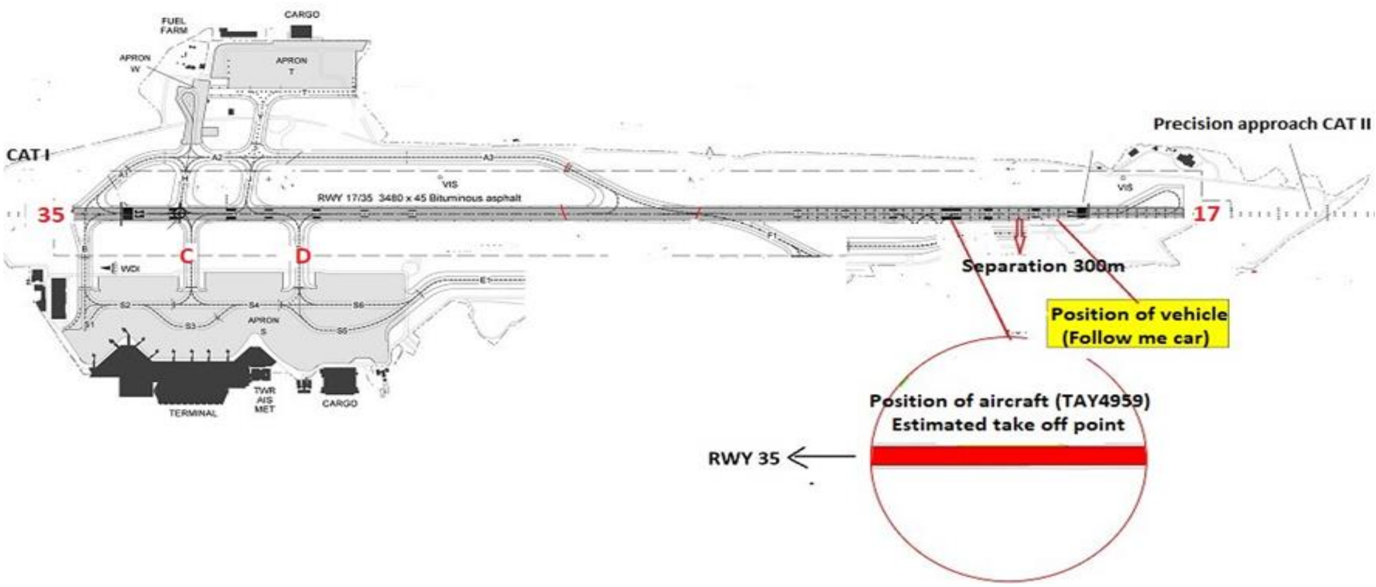

Figure 1. TAY4959, Path followed for Runway 35

On the day of the incident, follow-me vehicle made a call on the handheld radio and asked for permission from the controller to enter Runway 35 from Taxiway 'B' in order for inspection. In the meantime, the controller continued to work under a heavy workload because the frequency clearance for taxi, taxiing and take off were given on the same frequency due to frequency merging. 10 minutes later than the vehicle had entered runway 35 for routine controls, TAY4959 asked for clearance for taxi on runway 35 holding point and an intersection departure from taxiway D and this request was approved by the controller, and TAY4959 was given clearance to take off from Runway 35 at Intersection D. When TAY4959 was given clearance to take off from the D taxiway intersection, the follow-me vehicle had reached the end of Runway 35 and started to turn around to head south and inspect the remaining part of the runway. 15 seconds after TAY4959 had started to take off run, the driver of the follow-me vehicle informed the controller through handheld radio that he was seeing bright lights coming towards him. While the controller and the driver of the follow-me vehicle were communicating, TAY4959 took of moments before reaching the follow-me vehicle as it can be seen in Figure 1. Due to the absence of stopbar lights during the incident also reduced the situational awareness of the controller, pilot and the driver of the vehicle (GPIA, 2021).

Factors that caused the incidents are;

Lack of teamwork:

- On the day of the incident, controller on-duty had been working continuously for four hour managing all frequencies alone and issuing clearance, taxi, and takeoff instructions by himself.
- Planning of the controller involved in the incident as a supervisor and a team leader was based on personal preferences which were far from concepts like tactical management of the team, determining the number of staff and creating risk analysis.

Organizational effects/ Organizational functioning:

- Since there was no audio/visual warning system that could remind the controller that there was a vehicle on the runway reduced the situational awareness.

Unsafe monitoring:

- Not having stopbars on junction points and the entrances on the runways reduced situational awareness.
- Not having an efficient runway incursion monitoring and conflift warning system decreased situational awareness.

Lack of communication:

- The communication of aircraft and follow-me vehicle with the controller occurred at different radio systems (tower frequency and handheld radio) and therefore, this prevented the pilot and the follow-me vehicle from being aware of each other on the runway.

Lack of positive safety culture/ Failure to report previous similar incidents:

- Although there had been similar incidents before, the unsafe incident was not reported to safety management unit officially.
- Unsafe behaviors were triggered because people have different understanding of working and risk culture, organizational culture and safety culture.
- The existence of an individual and organizational culture based on concealment, and the failure to establish a safety system based on risk assessment by the organization to ensure that safety is not compromised, were the effective factors in the occurrence of the incident.

Stress and chronic fatigue:

- Working continuously without sufficient rest time caused excessive fatigue for the controller.

2.1.2. Incident 2

On November 14, 2019, an Air Algerie flight (callsign AH1157), a scheduled international passenger flight from Lyon Saint-Exupéry to Annaba, Algeria, operated by a B738 aircraft, started its takeoff roll on Runway 35L while low visibility procedures (LVP) were in effect. The controller working in the tower position saw that snowplows had entered the active runway and rushed to instruct AH1157 to stop immediately. This serious incident was caused by the ground controller (who manages ground movements and separations) granting the vehicle permission to enter the runway without prior coordination with the tower controller (who grants landing and takeoff clearances). 15 minutes before the incident happened, tower (landing and takeoff service position) and approach (service position for traffic below a certain altitude) services were provided on a single frequency by the same controller, by merging the frequencies. At the moment the ground controller granted pushback and start-up clearance to the AH1157 traffic preparing for takeoff, the leader vehicle with the callsign ELEC8 and another accompanying snowplow requested permission via handheld radio to enter Runway 35L to clear accumulated snow from the runway and taxiways. The ground controller authorized the snowplows to work on Taxiway A3, cautioning them to watch for landing aircraft. Meanwhile, another vehicle was also permitted to be on the runway for brake measurements (BEA, 2022).

The positions of the vehicles are shown in Figure 2.

Figure 2. Lyon Saint-Exupéry Airport 17R/35L Runway and Taxiways

As the ground controller granted taxi clearance to AH1157 to Taxiway A9 CAT III holding point for Runway 35L, the ELEC8 snowplows reported that they would be clearing snow from Taxiway A4 and then intended to clear the A4 and runway intersection. When AH1157 was at A9 holding point on tower frequency, "ELEC8" contacted ground controller and stated that they would continue clearing snow from A4 taxiway and its intersection with the runway. The ground controller instructed ELEC8 to enter Runway 35L and authorized them to clear the area marked as blue zone number 5 in Figure 2. Thirty seconds after the vehicle group led by ELEC8 entered the runway, the tower controller instructed AH1157 to begin takeoff while holding at red point 4 on the runway. Five seconds after AH1157 started its takeoff roll, the tower controller noticed the vehicles at blue point 5 on the runway and urgently instructed AH1157 to abort the takeoff (BEA, 2022).

It is possible to summarize the factors that caused the incident as below.

Lack of teamwork/Workload:

- The conflict of the roles in the tower and high workload.

Lack of communication:

- The controllers had learned that snowplows needed to enter the runway in order to clear the snow on the runway in the middle of the operation.
- Ground controller granted the runway entry permission which should have been given by tower controller without having the necessary communication with the tower controller on his own initiative.

Organizational functioning:

- Not having a clear framework related to the use of frequencies for vehicles during temporary runway closures.
- The rules for organizing and suspending operations that are difficult to implement for people directly involved in traffic management and snow removal.
- Having a snow clearance plan whose description is quite formal and which is partially disconnected from operational realities.
- Incorrect measurements of runway surface conditions that cause high workload and difficulties in implementing the snow clearance strategy.
- Organizational factors such as stopbar configurations that are not compatible the paths followed by snowplow vehicles contributed to the occurrence of this serious incident.

Lack of positive safety culture/Failure to report previous similar incidents:

- Although there had been similar incidents before, the unsafe incident was not reported to safety management unit officially.
- The existence of an individual and organizational culture based on concealment, and the failure to establish a safety system based on risk assessment by the organization to ensure that safety is not compromised, were the effective factors in the occurrence of the incident.

Stress and chronic fatigue:

- Working continuously without sufficient rest time caused excessive fatigue for the controller.

2.1.3. Incident 3

The incident occurred on runway 24R, which was being used for single-runway operations at Palma de Mallorca Airport, where there are two runways known as the north runway (06L-24R) and the south runway (06R-24L). It happened when a Boeing 737-800 of Ryanair (callsign RYR81SN) began its takeoff run and encountered a vehicle on the runway. Due to low traffic flow during the time of the incident, tower control, ground control and clearance services were provided on a single frequency. As it is seen in Figure 3, RYR81SN (B738 type) stated that it is ready to take off from 24R runway and clearance was granted for entry onto runway 24R. At the same time, follow-me vehicle contacted controller to demand entry to north runway from H5 taxiway, however; it mistakenly requested clearance to enter the southern runway instead of the northern runway. Despite "clear" instruction the of the controller, the follow-me vehicle informed the controller that the stopbar lights were on and needed to be turned off. Nevertheless, the controller stated that follow-me vehicle could ignore these lights and repeated the clearance to enter the runway. In the meantime, RYR81SN requested takeoff clearance, and the controller issued a takeoff clearance from runway 24R while the traffic was at position 2. Meanwhile, the Follow-me vehicle driver, who was listening to the frequency, called the tower to inform them that the vehicle was still on the runway. The controller issued an immediate stop instruction to the traffic with the callsign RYR81SN while it was at position 3. Although RYR81SN had reached takeoff speed, the aircraft responded to the call of the controller and managed to stop at position 4 (CIAIAC, 2020).

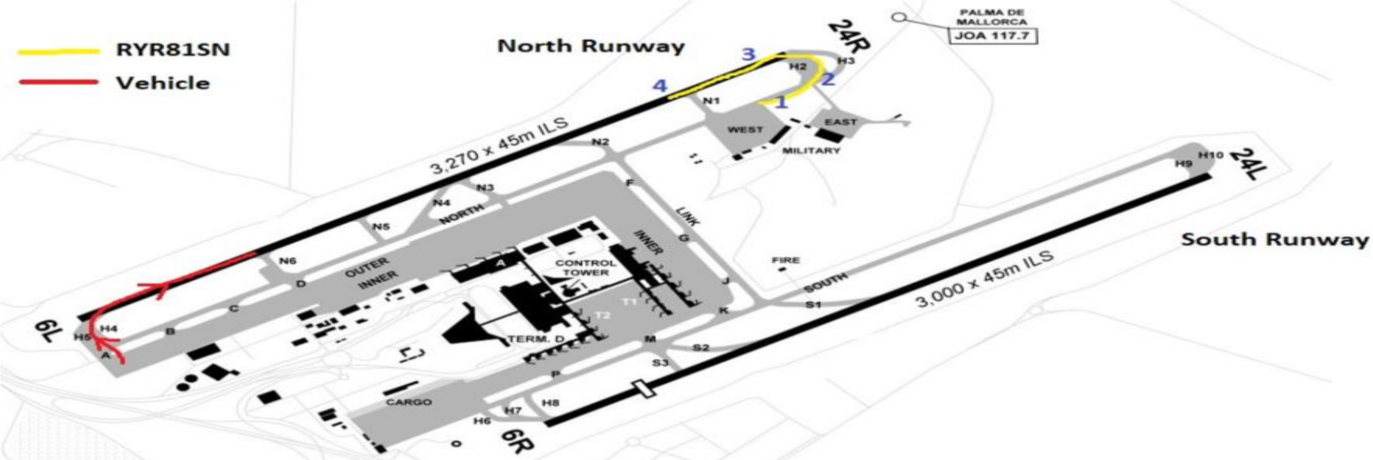

Figure 3. Palma de Mallorca Airport 06R-24L Runway and Taxiway

Factors that caused the incidents are listed below.

Lack of teamwork/ Situational awareness:

- The controller had combined tower/ground/ clearance sectors and working on his own which led lack of team support and resulted in errors.
- The inability of controller to visualize the position of the vehicle affected his control over the traffic negatively.

Lack of communication:

- Although the initial communication between the vehicle driver and the tower controller regarding the position and intent of the vehicle was confusing, the controller made no attempt to prevent the runway incursion. Instead, the controller allowed the vehicle to pass over the illuminated H5 stopbar lights and enter the active runway without any intervention, leading to the serious incident.

Organizational functioning:

- Using north/south in order to describe the runway caused an error in the way the vehicle driver referred to the runway he intended to access. The locational error made by the vehicle driver, requesting access to a runway that couldn't be reached from H5 during their initial communication at H5, went unnoticed by the controller for this reason.

Stress and chronic fatigue:

- Working alone caused the controller to feel mentally tired.

Lack of positive safety culture/ Failure to report previous similar incidents:

- It was confirmed that there had been similar unsafe incidents related to the use of stopbar lights and they were not reported.

2.1.4. Incident 4

On April 10, 2018, an incident occurred between a GOL Aviation B738 (callsign GOL2311) that had started its takeoff roll at night from Brasilia, and a Brazilian Air Force E110 (callsign FAB2345) that had just landed on the same runway and had not yet vacated it. After landing, when the FAB2345 reached taxi speed and, was at position 1 (Figure 4), indicated its intention to vacate the runway via taxiway C. However, the controller, seeing that the FAB2345 had passed taxiway C, instructed the FAB2345 traffic to vacate the runway via taxiway G and to switch to the ground control frequency. However, as it can be seen in figure 4, due to the visual similarity of the names on the signage of G and C taxiways, and the faded condition of signage of taxiway G, the FAB2345 mistook the taxiway G thinking that it is taxiway C. Consequently, at position 2, it continued to position 3 (F taxiway) thinking that the next runway exit was taxiway G and switched to ground control frequency. Since tower controller did not have a comprehensive runway view between G and F taxiways due to the woodland shown in figure 4, the controller granted takeoff clearance to GOL2311 when FAB2345 was at position 3 believing that FAB2345 had exited the runway via taxiway G (CENIPA, 2018).

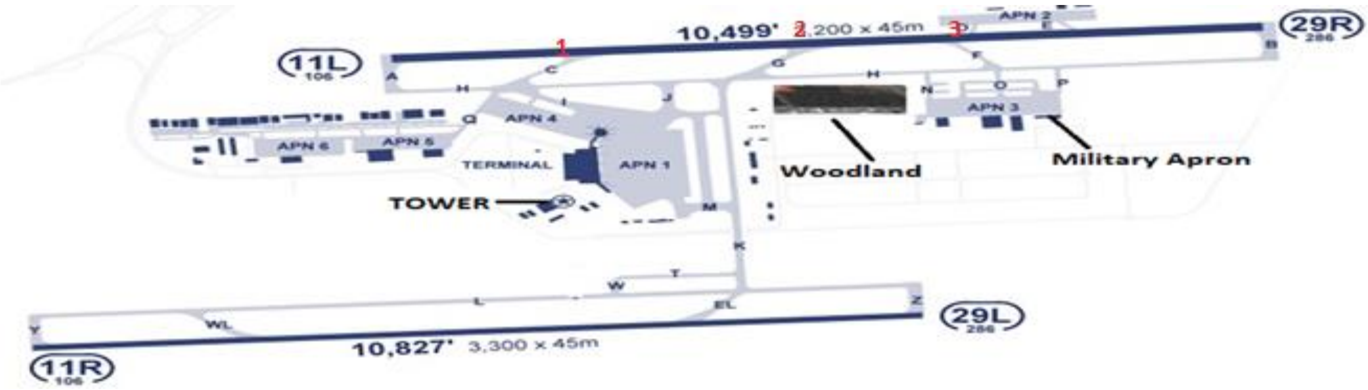

Figure 4. Brasilia Airport 11L/29R Runway and taxiways

It is possible to summarize the factors that caused the incident as below.

Lack of teamwork:

- The working position of the tower controller and external environmental conditions prevented the controller from seeing the aircraft with the FAB2345 callsign, and the ground controller was unable to determine the position of FAB2345 during their initial contact on the frequency. The lack of team work between the tower and ground controllers, and the absence of a third controller monitoring them, were among the latent factors contributing to the incident.

Lack of communication:

- Although the tower controller did not fully understand the initial call from FAB2345 after landing, they did not request a repeat and attempted to analyze the situation based on the location of the aircraft.
- Although FAB2345 had switched ground control frequency before exiting the runway, this situation was nor reported to tower controller by the ground controller.
- Deficiencies occurred in verbal communication between the tower and ground controllers regarding the actual position of FAB2345 after landing.

Organizational factors and / Organizational functioning:

- Not having a ground radar,
- Inability of the tower controller to track traffic effectively due to obstructions that blocked the visual view from the tower,
- Factors such as the lack of a regulatory requirement to define the position at which an aircraft should switch its frequency from tower control to ground control directly contributed to the occurrence of the incident.

Lack of positive safety culture/ Failure to report previous similar incidents:

- It was confirmed that there had been similar communication problems between tower control and ground controls previously, however; no precautions were taken related to this situation.

2.1.5. Incident 5

On July 27, 2018, at Amsterdam Schiphol Airport, the tower controller granted runway entry permission to the E190 aircraft of KLM Royal Dutch Airlines (callsign KLM1289) to runway 18C, as shown in Figure 5. At the same time, the controller permitted the B738 aircraft (callsign KLM1783) to enter the runway via taxiway W4. Approximately one minute later, the tower controller authorized KLM1289 to take off from runway 18C.

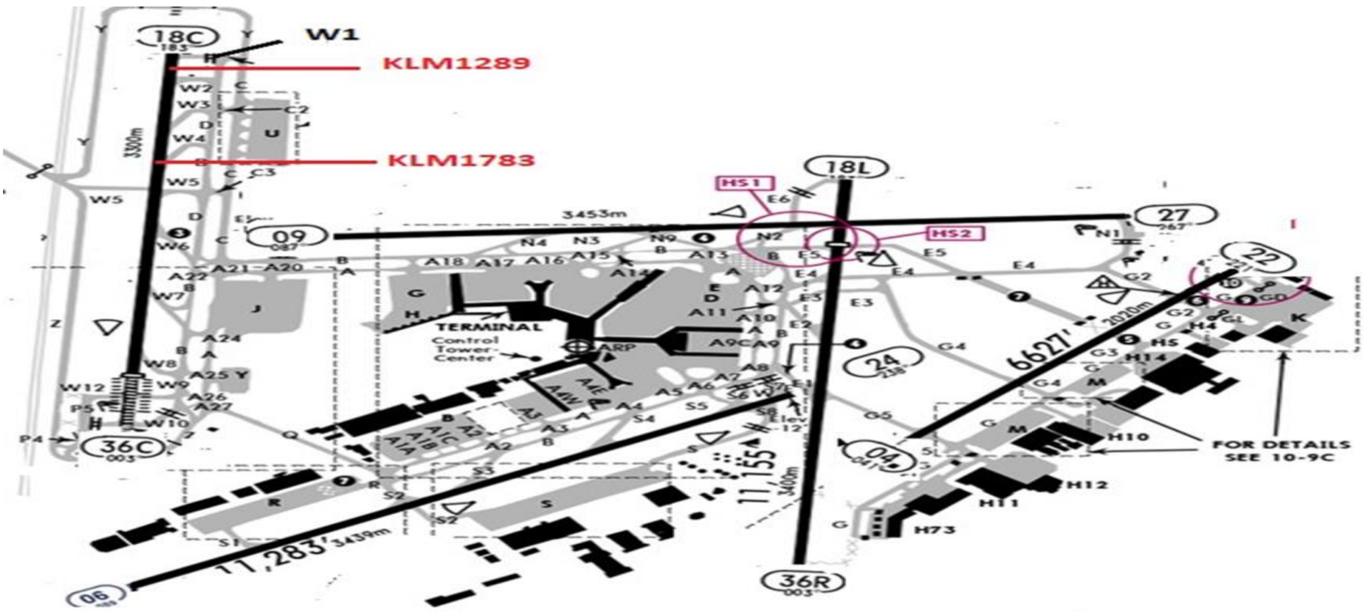

Figure 5. Amsterdam Schiphol Airport 18C/36C Runway and Taxiways

During the incident, while the runway 22 was being used both for takeoff and for landing, the runways 09 and 18C were just being used for takeoffs. Tower controller was providing traffic services for three active runways: 09, 18C and 22. As shown in figure 5, the incident occurred in 18C runway for which the controller provide takeoffs and landing services. At the time of the incident, KLM1289 reached 18C runway start point via W1 taxiway and KLM1783 reached intersection departure point via W4 taxiway. The tower controller had granted takeoff clearance to KLM1783 before the two other aircraft ready for departure, but since KLM1783 was moving slowly while turning onto the W4 intersection, it had not yet begun its takeoff roll. The tower controller, who forgot that he had already granted takeoff clearance to KLM1783, gave takeoff clearance to KLM1289 from the 18C runway heading about 2 minutes later. Upon hearing that KLM1289 was cleared for takeoff, KLM1783, which had passed the W4 holding point, stopped just before entering the 18C runway. KLM1783, which was stopped at the runway intersection, informed the tower controller that they were "on the runway." However, the tower controller, confusing the traffic, issued a takeoff clearance to KLM1783 from the W4 intersection. Hearing that KLM1289 was also cleared for takeoff from the 18C runway heading at the same time, KLM1783 did not proceed with the takeoff clearance and maintained its position. The pilots of KLM1783 could not see the runway threshold 18C due to the angle of the W4 intersection taxiway. Thirty minutes before the incident, two separate events involving the same tower controller were recorded. The first incident involved a light aircraft with VFR clearance that posed a brief risk to traffic taking off from the 18C runway. Then, 20 minutes before the incident, the controller granted takeoff clearance to one aircraft from the 18C runway but also permitted another aircraft to taxi to the 18C runway via the W4 intersection (DSB, 2018).

The factors causing the incidents are below.

Lack of teamwork:

- The absence of controller to assist tower controller during periods of intense workload.
- Absence of an additional controller in the tower to monitor the traffic contributed to the occurrence of the incident in terms of teamwork.

Organizational factors/ Organizational functioning

- Due to the lack of written rules, the controller continued to work despite having experienced two previous incidents before the serious one,
- The incorrect configuration of runways for landing and takeoff,
- The management of 09, 18C and 22 runways by a single controller,
- The fact that KLM1783, which entered the runway from taxiway W4, could not see the traffic on the runway due to the intersection of the taxiway were among the factors that contributed to the occurrence of the incident.

Lack of communication

- In the busy and complex runway structure, the ground controller asking KLM1783 whether it could take off from taxiway W4 to expedite traffic, and increased workload of the tower controller were observed as factors contributing to the communication deficiencies leading to the incident.

Lack of positive safety culture/ Failure to report previous similar incidents

- It was understood that the controllers continued working despite experiencing similar incidents before the serious event, and no regulations were implemented to address the issue of controllers not actively working during such distracting situations.

2.1.6. Incident 6

On September 22, 2017, at Hong Kong International Airport, a runway incursion occurred when an Air Cargo Global aircraft (call sign CCC831), a B744 type, crossed the runway from J6 Taxiway just as a Hong Kong Airlines A333 aircraft (call sign CRK236) began its takeoff roll on Runway 07R. The pilots of CRK236 immediately aborted the takeoff upon noticing another aircraft crossing the runway. At the time of the incident, the controller, who was an instructor at the ground control position, was providing training to a trainee controller. Throughout the roughly one-hour period of ground control operations, the instructor controller occasionally took over the position when traffic increased or the trainee controller struggled, before handing it back to the trainee. After the CCC831 traffic, as indicated in Figure 6, landed on runway 07L, it exited the runway and switched to ground control frequency, where it was instructed by the ground controller to taxi via A, W, J, and J6 holding point. When CCC831 arrived at J6 taxiway, the ground controller, due to not fully understanding the position of the aircraft, did not transfer CCC831 to the frequency of the tower controller for the runway crossing and instead instructed the aircraft to taxi via K and L2 taxiways to its parking stand. At the same time, tower controller, unaware that CCC831 was crossing runway 07R, granted takeoff clearance to CRK236. As CRK236 began its takeoff roll and reached the vicinity of taxiway K2, crossing traffic was spotted the and the takeoff was immediately aborted (AAIA, 2021).

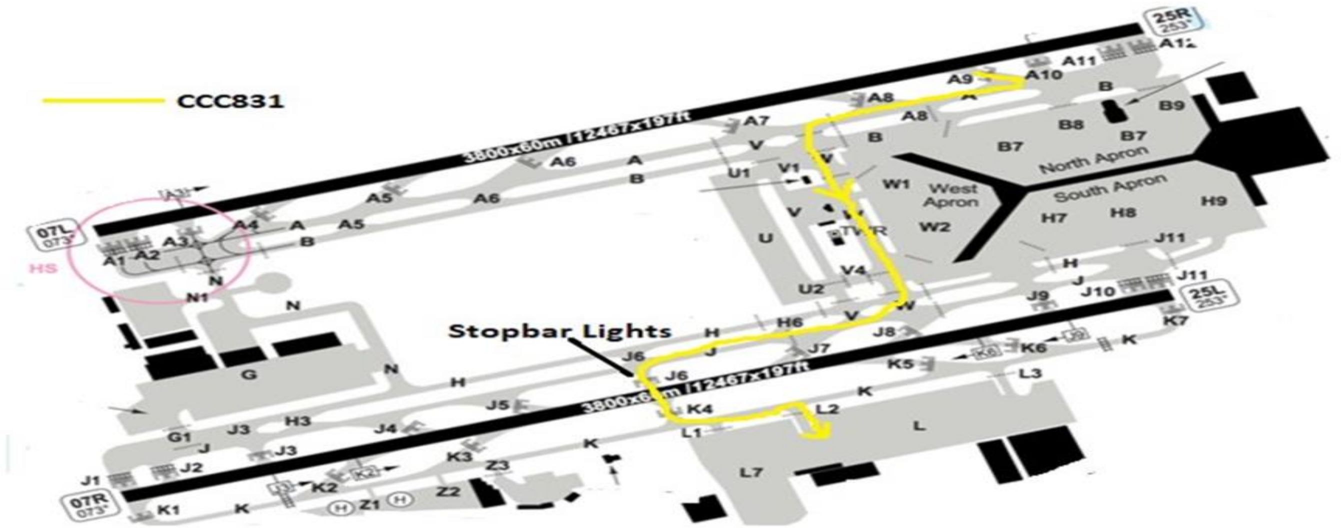

Figure 6. Hong Kong International Airport 07L/25R and 07R/25L Runways and Taxiways

The factors leading the incidents are listed below.

Lack of teamwork/ Situational awareness:

- The frequent handover of the ground control position between the instructor controller and the trainee controller, based on traffic intensity, reduced their situational awareness of the traffic positions.

Unsafe Monitoring:

- At the time of the incident, it was determined that the traffic conflict audio alert on the ground radar was inactive in both the tower control and ground control positions.

Lack of Communication:

- Although runway crossings should be managed on the tower frequency, CCC831 at the J6 holding point was not transferred to the tower frequency
- The ground controller only cleared CCC831 to proceed to the parking area via taxiways K and L12, without using the necessary runway crossing clearance expression, and there was no clear feedback by the pilots.

2.1.7. Incident 7

On March 17, 2017, at Lyon Saint-Exupéry Airport, after landing on runway 35R, the CRJ700 aircraft of Air France Hop (callsign HOP83A) was cleared to cross runway 35L as shown in Figure 7. At the same time, an A319 aircraft of EasyJet (callsign EZY748Z) was cleared for takeoff from runway 35L. During the incident, the tower controller gave the takeoff clearance to EZY748Z from runway 35L in English, as shown at the blue point 2 in Figure 7. Thirty seconds before this, the controller also cleared HOP83A, located at the red point 3, to cross runway 35L in French. As EZY748Z began its takeoff roll from runway 35L, HOP83A, which was crossing the runway, noticed the departing traffic and managed to make an emergency stop at the red point 4 (BEA, 2020).

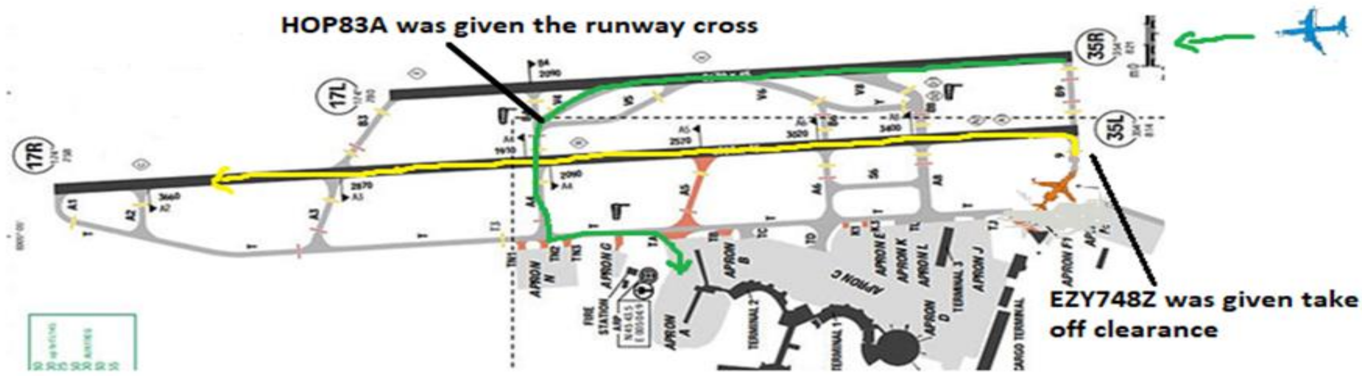

Figure 7. Lyon Saint-Exupéry Airport17L/35R and 17R/35L Runways and Taxiways

The factors leading the incidents are listed below.

Lack of teamwork/ Situational awareness:

- Failure to control the runway by the tower controller and his low situational awareness
- Heavy air traffic led the tower controller to issue instructions quickly and prematurely, and the absence of another controller to observe or share the workload contributed to the occurrence of the serious incident.

Lack of communication:

- The fact that the crossing traffic HOP83A communicated in French and the departing traffic EZY748Z communicated in English resulted in EZY748Z not understanding the position of the crossing traffic.

Organizational factors/ Organizational functioning

The malfunctioning of the stopbar lights on taxiway B4 prevented the controller from realizing his mistake.

Lack of positive safety culture/ Failure to report previous similar incidents:

- It was found that similar misunderstanding had occurred in the past due to speaking French instead of English at times, but no safety measures had been implemented to address this issue.

2.1.8. Incident 8

On December 2, 2016, at Calgary Airport, as shown in Figure 8, an incident occurred when a Fairchild-Swearingen Airlines SA226 (callsign CFGEW) crossed runway 29 from the midpoint, coinciding with an encounter on the runway with an A320 Air Canada aircraft (callsign ACA221) that had just begun its takeoff run.

Figure 8. Calgary Airport Runways and Taxiways

At the time of the incident, runway 29 was in use, but the runways had changed several times throughout the day due to wind conditions. As seen in Figure 8, the tower controller gave ACA221 clearance for takeoff from position 3 (indicated in red) while, simultaneously, the ground controller granted CFGEW clearance to cross the runway. The urgency of the ground controller in clearing the crossing stemmed from the desire to quickly separate CFGEW from another CRJ900 traffic at the intersection of taxiways A and J. The pilots did not have the opportunity to intervene in the situation because ACA221 was on the tower frequency and CFGEW was on the ground control frequency (TSB, 2018).

Factors that caused the incidents are these.

Lack of teamwork/ Situational awareness:

- It is clear that the situational awareness of the two controllers is low because both the ground controller and the tower controller issued instructions to aircrafts without proper environmental monitoring.
- Not having a supervisor at the tower to follow the incidents caused the incident to occur.

Lack of communication:

- Rarely use of runway 29 throughout the day prevented ground controller to transfer CFGEW to tower frequency for clearance to cross the runway. The ground controller laid the groundwork for the incident by granting clearance for crossing without coordinating or transferring the frequency to the tower controller, as it is required for crossings.

Unsafe monitoring:

- The lack of stopbar lights at crossing points 6 and 8 in Figure 8 reduced the awareness of the pilots.

Teamwork/Workload:

- The excessive separations by the ground controller and the absence of a supporting team member led to the ground controller hurrying and making decisions without careful consideration.

Lack of positive safety culture/ Failure to report previous similar incidents:

- In similar past incidents, the fact that traffic was on different frequencies despite needing to be on the same frequency, combined with the lack of established procedures for such situations, was one of the causes of the incident.

2.1.9. Incident 9

On January 7, 2016, at Gran Canaria Airport, a Germania Airlines B737 (call sign GMI6129) began its takeoff from runway 03R with the permission of the tower controller, but the takeoff was canceled by the same controller upon noticing an object on the runway. During the incident, while at position 1, as shown in Figure 9, GMI6129 was instructed by the tower controller to cross runway 03L. When GMI6129 reached position 2, the crew reported that the stop bar lights were illuminated and maintained their position. Despite this, the tower controller granted GMI6129 clearance to enter the runway and take off. Although GMI6129 saw a vehicle on the runway immediately to its right after receiving the takeoff instruction, it continued the takeoff run, thinking the vehicle did not pose an obstacle. When GMI6129 reached position 4, the tower controller noticed another vehicle in the middle of the runway, canceled the take off of GMI6129 and GMI6129 was able to stop at position 5 after it had been instructed to cancel its take off. On the day of the incident, automatic ATIS (Automatic Terminal Information Service) broadcast continuously announced that 03R runway was closed due to construction (CIAIAC, 2016).

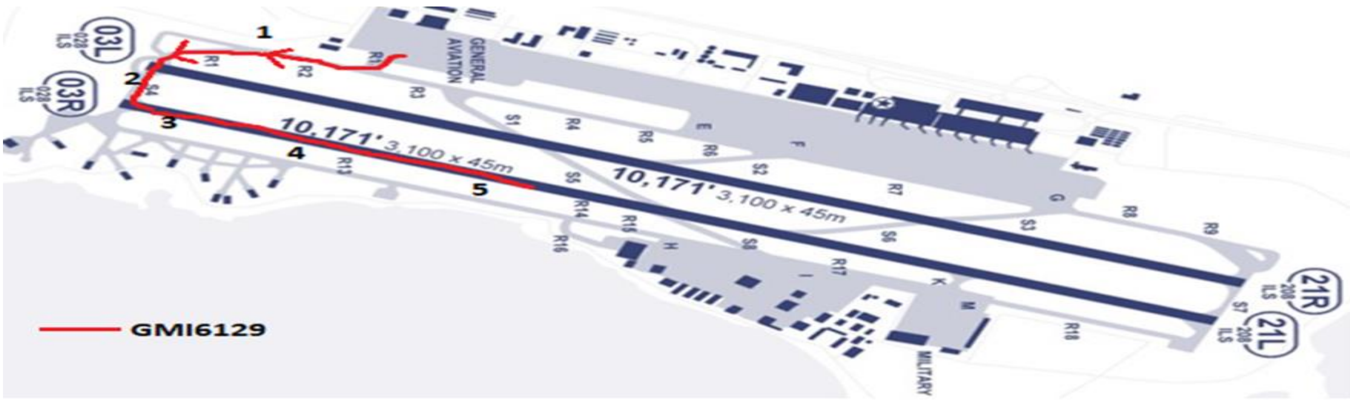

Figure 9. 03L/21R and 03R/21L Runway and Taxiways

Factors leading the incident are listed below.

Lack of teamwork/ Situational awareness:

- Although there were visual aids in the tower to show that the runway was closed, the controller could not perceive that the runway was closed. The inability of the controller and pilots to see the vehicle on runway 03R was attributed to the lack of flashing lights on the vehicle. Despite being in visual contact with the vehicle stopped on the runway strip, GMI6129 began its takeoff roll. Although the situational awareness of the controller was poor, they did not receive sufficient support from their team members.

Lack of communication:

- Although the controller partially heard the report from GMI6129 about the illuminated stop bar lights, they did not ask the pilot to repeat the message and instead instructed GMI6129 to enter runway 03R again. The fact that GMI6129 did not request the controller to turn off the stop bar lights and proceeded onto the runway despite the illuminated lights also contributed to occurrence of the incident.

Organizational functioning:

- The fact that the vehicles operating on the NOTAM (Notice to airman) designated runway did not have lighting and flashing lights at a level that would attract the attention of the pilot and controller indicates an organizational deficiency.

2.1.10. Incident 10

The incident occurred on October 12, 2014, at Addis Ababa Airport when Ethiopian Airlines (flight ET805), a B763 aircraft, started its takeoff roll on runway 07R and spotted a vehicle in the middle of the runway, leading to the cancellation of the takeoff and stopping approximately 100 meters from the vehicle. Air traffic control services at the airport were provided by two controllers, one on the ground frequency and one on the tower frequency, using runway 07R, which is 3,800 meters long and 45 meters wide. There was no supervisor in the tower since it was a Sunday and supervisors were not on duty on weekends. A departing aircraft reported flocks of birds on the parallel runway 07L/25R, and bird activity was also observed by the ground controller on the taxiway and parallel runway. As a result, it was decided to deploy bird dispersal teams to the maneuvering areas. The ground controller wanted to inspect runway 07R, which was in use after 07L/25R, as shown in Figure 10. After verbally obtaining approval from the tower controller, the ground controller allowed the bird dispersal vehicle onto runway 07R. After completing the first section of inspection, the bird dispersal vehicle turned back from the threshold of runway 25L and arrived at the blue position 1, as shown in Figure 10. Meanwhile, the ground controller directed ET805 to the holding point of runway 07R and handed it over to the tower frequency.

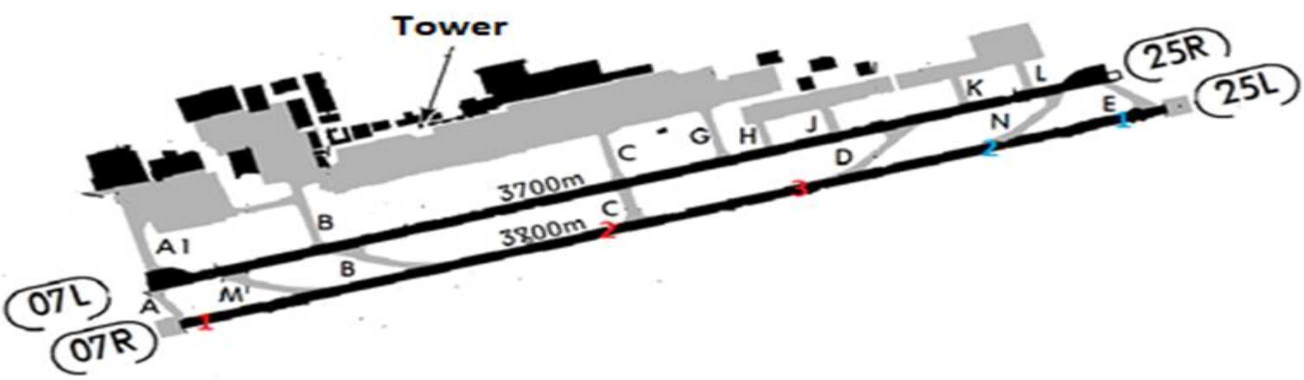

Figure 10. Addis Ababa airport 07L/25 R and 07R/25L Runway and Taxiways

The tower controller granted ET805 clearance for takeoff from runway 07R at the red position 1, and the aircraft began its takeoff roll. When the aircraft reached V1 (138 knots) and arrived at red position 2, the crew noticed a vehicle on the runway at blue point 2. They immediately applied brakes and managed to stop at red point 3. When ET805 stopped, it was 100 meters away from the vehicle. The sudden braking caused the brakes to overheat, resulting in the blowout of four tires, and ET805 had to be towed to the parking area by a tug (ECAA, 2014).

It is possible to summarize the factors that caused the incident as below.

Lack of teamwork/ Situational awareness:

- The tower needed to control the runway before granting clearance for take off and then it should have granted the clearance; however, necessary environmental control was not performed. The incident was caused by the low situational awareness of both ground and tower controllers.
- The absence of a third controller in the tower, who should have been monitoring the situation as part of the team, played a contributed to the failure to prevent the incident.

Lack of communication:

- During the post-incident investigation, the ground controller claimed to have received direct verbal approval from the tower controller for the bird dispersal vehicle to enter the runway, while the tower controller stated that there were errors in communication. The runway inspection clearance, which should have been given by the tower controller, was instead issued by the ground controller (ECAA, 2014).

Lack of positive safety culture/ Failure to report previous similar incidents:

- It was understood that the tower and ground controllers had previously managed traffic flow under the responsibility area of the tower through verbal communication. The failure to report such incidents in accordance with positive safety culture objectives created a basis for the occurrence of this risky event.

2.1.11. Incident 11

On April 4, 2016, at Jakarta Halim Airport, a Batik Air Indonesia Airlines B738 (flight ID7703) began its takeoff roll from runway 24 and noticed an object on the runway, prompting a maneuver to the right of the centerline. Despite veering slightly to the right of the runway centerline, the aircraft could not avoid wing contact with a towed ATR42 being pulled to the parking area from within the runway.

As shown in Figure 11, the ATR 42 was planned to enter from taxiway C, proceed across the runway, and exit via taxiway G to the apron on the other side of the runway. The ATR 42 was to be towed without any engine power, meaning there was no radio communication between the aircraft and the ground controller, and the lighting systems of the aircraft were not operational. Communication between the tow truck driver and the ground controller was maintained via handheld radio, which meant that ID7703, which was taking off, and the ATR 42 tow traffic were on separate channels.

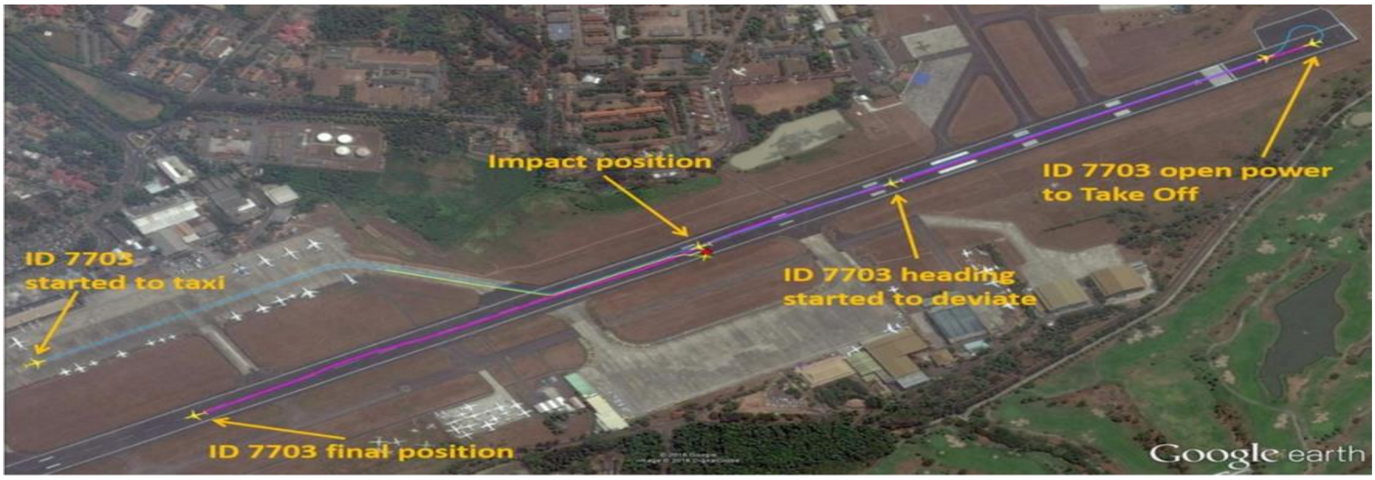

Figure 11. Jakarta Halim Airport 06/24 Runway and Taxiways (ANS, 2016)

After takeoff clearance was given to ID7703 on the tower frequency 118.6 MHz, as determined by the tower controller, permission was also granted by the assistant controller via handheld radio for the ATR 42 to be towed to the southern apron area (KNKT, 2016).

It is possible to summarize the factors that caused the incident are listed below.

Lack of communication:

- Conducting two ground movements in the same area on separate frequencies with different controllers and without proper coordination led to a lack of awareness among the controllers, pilots, and the towing vehicle driver about each other.

Lack of teamwork:

- Although two ground movements were conducted by different controllers on separate frequencies in the same area without proper coordination, the lack of verbal communication and coordination between them contributed to the incident. There was also a communication gap between the assistant controller and the towing vehicle. The misinterpretation of the instruction of assistant controller for the towing vehicle to follow ID7703 led to the towed aircraft entering the runway.

Organizational factors/ Organizational functioning:

- The controllers' ability to track the aircraft was difficult due to poor lighting inside the tower and reflections from the windows.
- The lighting conditions inside the tower cabin and in the turn area of Runway 24 diminished the ability of controllers and pilots to track the towed aircraft.
- The glare from the lighting systems of runway made it difficult to monitor movements on the runway.
- The fact that the AT42 was towed by a tug instead of using its own engine power meant that the lighting systems of the aircraft were not operational, making it difficult to track the aircraft.

2.1.12. Incident 12

On November 25, 2015, under daylight conditions, a B734 aircraft operated by TNT Airways (call sign TAY421J) was cleared to land on runway 02 by the tower controller, while the ground controller instructed an A321 aircraft operated by Air France (call sign AFR1449) to cross runway 02 via taxiway D2 (as indicated in Figure 12). As shown in Figure 12, when the ground controller granted AFR1449 clearance to cross runway 02, the stopbar lights at taxiway D2 were illuminated. The pilot, noticing the stopbar lights were on, reported the situation to the ground controller, but the ground controller reiterated the clearance to cross. With the awareness created by the stopbar lights, AFR1449, while monitoring its surroundings, reported to the ground controller that it was following traffic that was about to touch down on runway 02. Subsequently, the ground controller instructed AFR1449 to maintain its position. During the incident, TAY421J was on the tower control frequency while AFR1449 remained on the ground control frequency (CIAIAC, 2015).

Figure 12. Barcelona El Prat Airport 07L/25R and 07R/25L Runway and Taxiways

The factors causing the incident are below.

Lack of teamwork:

- Although air traffic control services are based on teamwork, the lack of team intervention regarding the persistent erroneous instructions of the ground controller contributed to the incident.

Lack of communication:

- The responsibility for the crossing traffic, AFR1149, should have been transferred from ground control to tower control at the D2 holding point and the crossing clearance should have been given by the tower controller. However, the crossing was authorized by the ground controller without any communication with the tower controller.

Lack of positive safety culture:

- One of the causes of the incident was the lack of sufficient knowledge about the operational principles of the stopbar lights at the relevant airport, and the fact that similar incidents involving stopbar lights had not been reported.

2.1.13. Incident 13

The incident occurred on July 10, 2014, at Port Elizabeth Airport in South Africa, during daylight conditions. As the South African Airways A320 (call sign SAA410) began its takeoff roll from runway 26, the Expressways CL600 aircraft (call sign EXY336), which was approaching runway 26 and was 1 NM from touchdown, decided to go around and executed a right maneuver to ensure its own separation, as indicated in Figure 13.

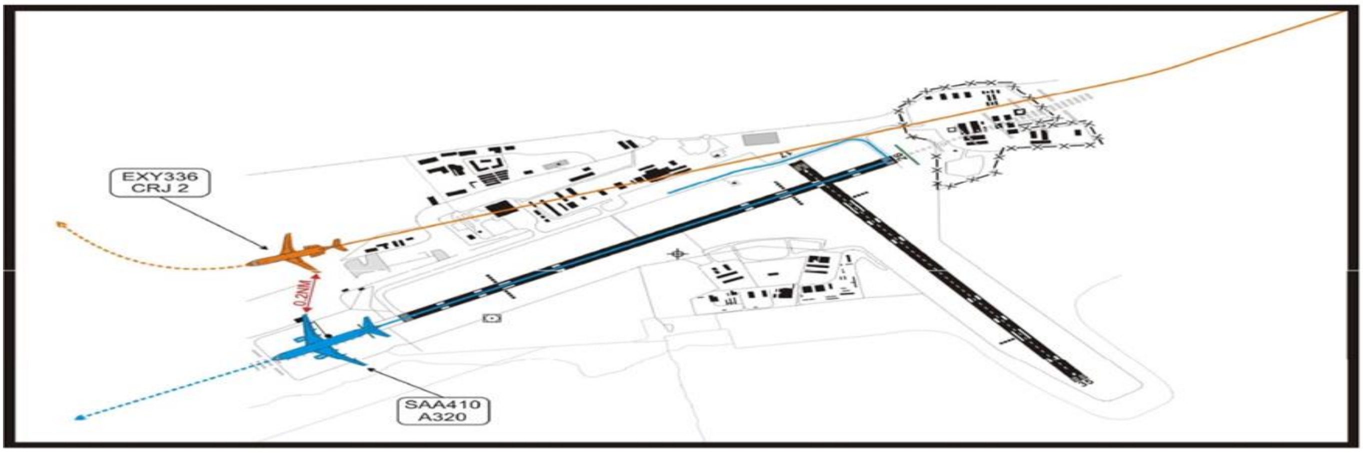

Figure 13. South Africa Port Elizabeth Airport 08/26 and 17/35 Runways and Taxiways (SACAA, 2014)

In addition to not having enough controller at the tower at the time of the incident, there was also a trainee controller on training. EXY336 was approaching Runway 26 visually due to the ILS system being controlled by the flight control aircraft. When SAA410 approached Runway 26, it indicated that it was ready for an immediate departure. Although EXY336, which the tower controller had previously contacted but forgotten, was 2 NM away from the touchdown point, the controller granted SAA410 permission to enter and take off from Runway 26. At the same time, despite EXY336 indicating it was 1.5 NM away, the tower controller did not cancel the departure of SAA410 and instructed EXY336 to continue its approach. As the landing traffic EXY336 passed 1 NM, it decided to go around upon observing that SAA410 was still at the beginning of the runway. The controller instructed EXY336 to turn left and also provided information about the flight control aircraft waiting in the southern part of the airport. However, both the bypassing EXY336 and the departing SAA410 received a TCAS RA. EXY336, performing a right avoidance maneuver, passed very close to the departing aircraft SAA410 with a horizontal separation of 0.2 NM and a vertical separation of 263 feet (SACAA, 2014).

Factors that caused the incident are below.

Organizational factors/ Organizational functioning:

- The low elevation of the control tower makes it difficult to monitor aircraft on the approach path.
- During clear skies, certain relatively small aircraft types, such as the CRJ series, are less visible compared to others when approaching Runway 26.
- On sunny days, reflections on the windows of the control tower reduce visibility and overall quality of sight.
- Although training for student and trainee controllers during busy periods should be conducted when multiple controllers are on duty, the failure to follow this procedure contributed to the occurrence of the incident as an organizational factor.

Lack of teamwork / Situational awareness:

- Although there was a local radar screen available for tower controllers, the failure to utilize the screen indicates a weakness in situational awareness.
- The statement of the tower controller that they were "busy instructing a student" when the incident occurred indicates a lack of teamwork.

Lack of positive safety culture / Failure to report previous similar incidents:

- The flight inspection aircraft performing ILS calibration flights and the of controller with the maneuvers of the flight inspection aircraft became a contributing factor to the occurrence of the incident. Despite similar incidents occurring previously due to calibration flights, no precautions were taken.

2.1.14. Incident 14

The incident occurred on July 26, 2014, when a QantasLink Airways B717 (call sign QJE1921) had to take off again after seeing a vehicle on runway 24, just six seconds after touching down at Perth Airport, Australia, during daytime and clear visibility conditions. During the incident, intersecting runways 21 and 24 were being used simultaneously for takeoffs and landings. QJE1921 was cleared for an ILS approach to runway 24. Shortly thereafter, a new controller took over the tower position, and soon after, QJE1921 inquired about the wind conditions on the tower frequency. The new controller noticed that the landing strip for the aircraft was marked as 21 on the strip, as shown in Figure 14, and changed it to 24. Subsequently, another A330 aircraft, on final approach to runway 21, was granted landing clearance.

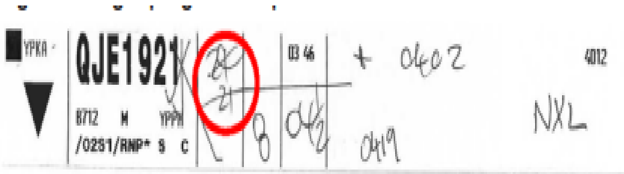

Figure 14. Landing Strip Arrangement for Traffic with Call Sign QJE1921 (ATSB, 2015)

Approximately at the same time, the "follow me" vehicle reported being ready at the holding point of runway 24 to perform a routine runway inspection. The tower controller permitted the vehicle to enter runway 24 but instructed it to hold at position 3, as shown in Figure 15, just before entering runway 21. When the follow me vehicle entered runway 24, QJE1921 was 7.5 NM away from the touchdown point of runway 24. Although communication with the follow me vehicle occurred on the tower frequency, none of the QJE1921 pilots heard the clearance for the vehicle to enter the runway.

The vehicle began to move along runway 24 in the direction of use and eventually held its position at the holding point before the intersection with runway 21. After the A330 landed on runway 21 and vacated it, the tower controller cleared another traffic, an F100, for takeoff from runway 21. Observing the takeoff of F100 from runway 21, the tower controller then cleared QJE1921, which was 1.5 NM away, for landing on runway 24 without seeing the vehicle on the runway. The vehicle driver later stated that they heard this clearance but assumed the aircraft was landing on runway 21.

As shown in Figure 15, when QJE1921 landed on runway 24, approximately 370 meters from the runway threshold, the co-pilot noticed the flashing lights of a vehicle at position 3 on the runway and reported it to the captain. The captain initiated a go-around and, after touching down on the runway and moving approximately 370 meters without slowing down, the aircraft took off again from position 5. Meanwhile, the safety vehicle was positioned on the centerline of runway 24, approximately 1180 meters from the threshold, facing the opposite direction of the approaching QJE1921. The driver of the vehicle did not see the aircraft until it passed about 150 feet over the vehicle (ATSB, 2015).

POINT	INCIDENT EXPLANATION
1	The point where the vehicle waited before entering Runway 24
2	The point where VHNXL got landing clearance
3	The point where the vehicle waited before entering Runway 21
4	The touchdown point of VHNXL
5	The point where VHNXL stated there was a vehicle on the runway
6	The point where VHNXL took off again
7	The point where VHNXL passed over the vehicle at 150 feet

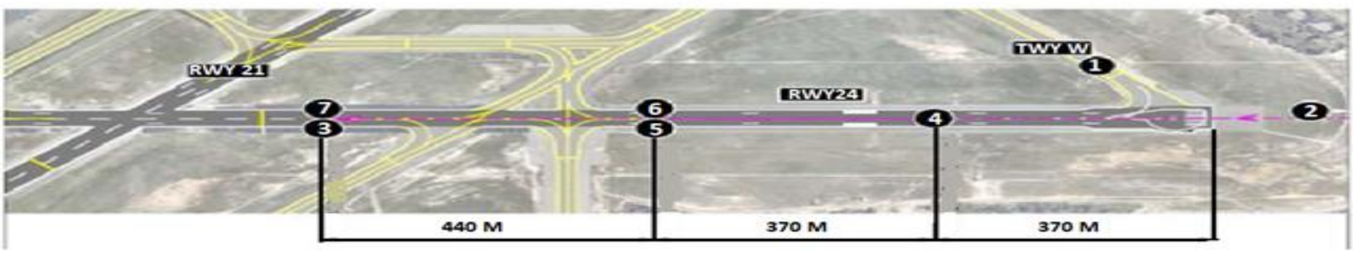

Figure 15. Australia Perth Airport 03/21 and 06/24 Runways and Taxiways (ATSB, 2015)

Factors leading the incident are below.
Organizational factors /Organizational functioning:

- Failure to have a ground radar,
- Insufficient strip arrangement,
- Insufficiency of vehicle lighting for runway operations
- The lack of runway inspections relative to oncoming traffic, resulting in the vehicle driver being unable to see the aircraft, has been observed as organizational factors contributing to the incident.

Lack of communication:

- The lack of handover between controllers and teamwork was one of the factors contributing to the incident.

Situational awareness:

- Low situational awareness of the tower controller was observed as another factor contributing to the incident.

2.1.15. Incident 15

On December 1, 2013, at Ottawa Macdonald airport, under night and normal visibility conditions, a Piaggio 180 aircraft with the call sign CGFOX, taxiing from the police apron to the 07 runway holding point, crossed the center of the 14 runway as Dash 8 aircraft of JAZZ Aviation, with the call sign JZA988, was beginning its takeoff from the 14 runway, as shown in Figure 16.

As shown in Figure 16, after completing the de-icing process, JZA988 requested taxi clearance to runway 07. The ground controller advised JZA988 to take off from runway 14 due to the long taxi route and the need for more space on runway 07, and cleared the aircraft to taxi to the holding point of runway 14, which was accepted by the traffic. At the same time, the aircraft with the call sign CGFOX, requesting taxi clearance from the police apron, was cleared to taxi to the runway 07 threshold via taxiways G, B, and C. Since the ground controller did not enter the details of CGFOX into the ground radar, the traffic could not be observed on the radar. When the tower controller cleared JZA988 for takeoff from runway 14 and the aircraft began its departure, CGFOX, which was taxiing via taxiway C, started crossing runway 14. Because JZA988 was a relatively small aircraft with a capacity of 60 passengers, it lifted off early, and no adverse incidents occurred (TSB, 2013).

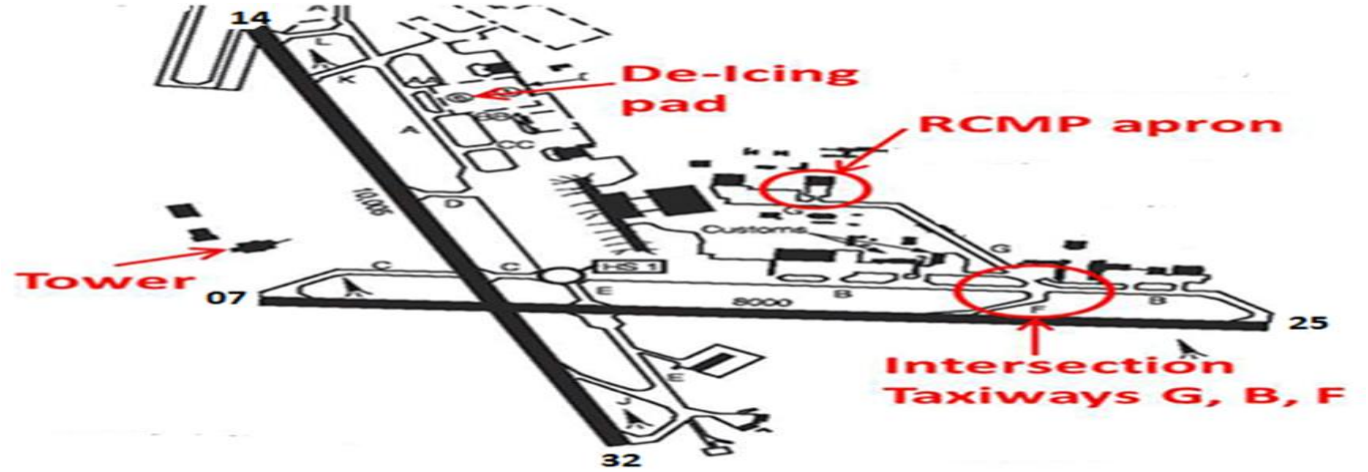

Figure 16. Ottowa Macdonald Airport 07/25 and 14/32 Runways and Taxiways

Factors that caused the incident are below.
Lack of communication:

- The failure of the ground controller to input information of CGFOX into the ground radar prevented the tower controller from tracking the traffic on the ground radar.
- The failure of the ground controller to transfer CGFOX, which crossed runway 14, to the frequency of the tower controller before the runway crossing, and his entry into the responsibility area of the tower controller, led to the runway incursion.
- The ground controller gave permission for the runway crossing, even though it was not their responsibility, and failed to inform the tower controller about the crossing.

Lack of teamwork / Workload:

- The ground controller, burdened by the workload of managing both ground movements and de-icing operations, issued instructions in an effort to quickly reduce their workload.

Lack of positive safety culture/ Failure to report previous similar incidents:

- Due to the failure of the ground controller to grant runway crossing clearance, similar incidents had occurred previously.

2.1.16. Incident 16

On October 3, 2013, under daylight and normal visibility conditions at Singapore Changi Airport, a Singapore Airlines B773 aircraft (call sign SQ371) that had just landed on Runway 20C observed a vehicle on the runway.

The ground controller instructed the vehicle operating under the call sign Rover 39 to proceed to a designated holding point on Runway 02C/20C and wait for three to four minutes, as indicated in Figure 17. Meanwhile, the tower controller was in communication with the ground controller and visually confirmed that the vehicle had reached the holding point. About a minute later, a third controller in a supervisor position, unaware of the previous clearance given by the ground controller but aware that the vehicle needed access to the runway to remove a dead bird, instructed the vehicle to be ready to enter the runway to collect the dead body of the bird. This communication was responded to by ROVER39 with the words "Understood, runway 20, thank you," and this feedback was not challenged by the supervisor. Following this clearance, the vehicle entered the runway. The stopbar lights, which should have been turned off when aircraft and vehicle crossings were allowed, were illuminated at the time the vehicle entered the runway.

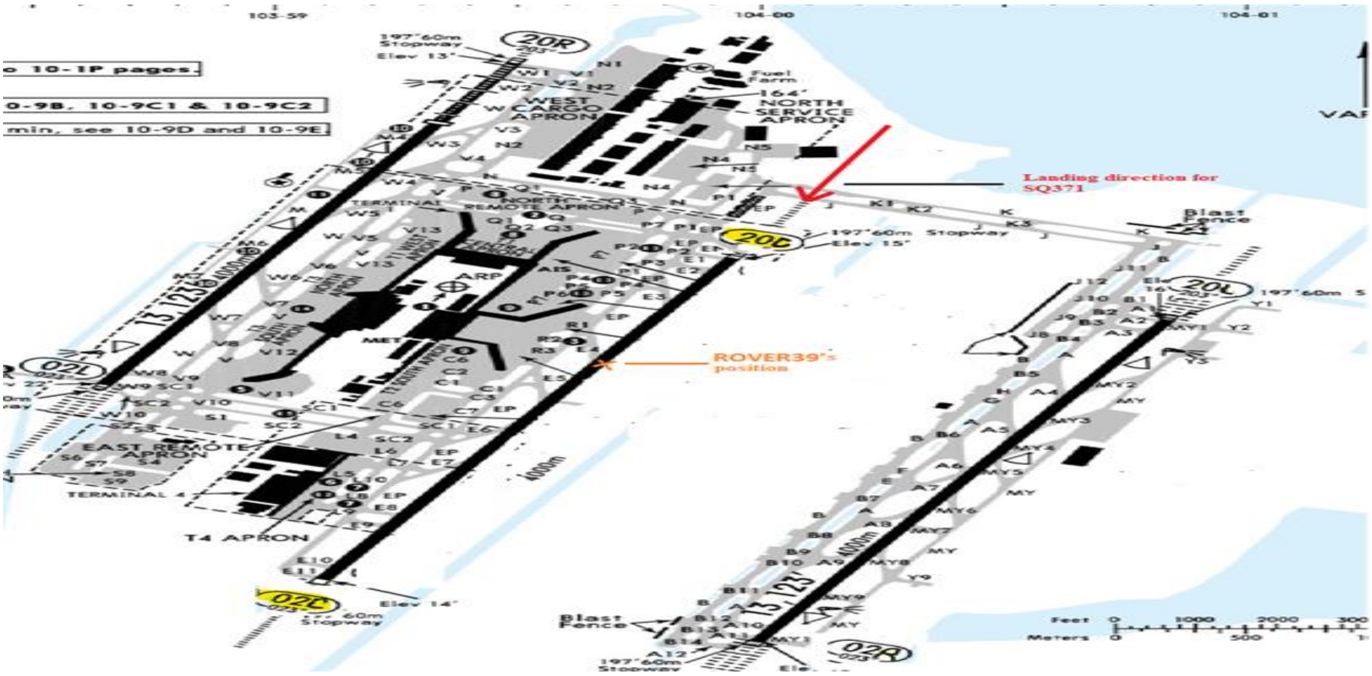

Figure 17. 02L/20R, 02/20C and 02R/20L Runways and Taxiways

Eight seconds after ROVER39 had entered the runway, tower controller granted clearance for landing to SQ371. The tower controller did not visually scan the runway or check the ground radar before granting landing clearance. Additionally, the controllers had frequently turned off the audio alert feature of the ground radar due to the frequent false warnings it gave. After SQ371 landed, the pilots noticed the vehicle on the runway near the E4 taxiway, as shown in Figure 17. They manually applied the brakes and veered slightly to the right of the centerline, allowing the wing of the aircraft to pass over the vehicle. It was found out that the vehicle in question was operated by a runway maintenance company contracted by the airport operator, and at the time, it was being driven by a driver who did not have the proper authorization to use a handheld radio (AAIB, 2013).

The factors contributing to the incident are as follows.

Lack of teamwork/ Situational awareness

- Tower and ground controllers failed to monitor the incident.
- The intervention of the supervisor in the operational position, rather than monitoring the incident by observing errors, was identified as a teamwork deficiency contributing to the incident.

Lack of communication:

- The runway entry permissions should have been granted by the tower controller. However, parts of these permissions were given by the ground controller and the supervisor, and the lack of communication between the tower, ground, and supervisor controllers contributed to the incident.

Organizational factors/ Organizational functioning:

- Although drivers entering the runway should have been sufficiently trained and authorized, the employment of unauthorized drivers for runway inspections revealed deficiencies in organizational procedures.

3. Result and Discussion

As part of the study, 16 serious incidents between 2012-2022 were analyzed by using content analysis. In these incidents, the factors contributing to unwanted events—such as lack of teamwork, communication deficiencies, organizational factors/functioning, lack of a positive safety culture, situational awareness, inadequate supervision, and stress and chronic fatigue—have been evaluated for the weight of their potential to cause accidents/incidents in air traffic control services. The criterion values obtained from the content analysis are tabulated as shown in Table 1.

Table 1. Content Analysis Criteria Weight

Criterion	Criterion Weight	%
Lack of Teamwork	3.68	23
Lack of Communication	3.68	23
Organizational Functioning	2.72	17
Lack of Positive Safety Culture	2.40	15
Situational Awareness	2,24	14
Inadequate Supervision	0.64	4
Stress and Chronic Fatigue	0.64	4
Total Number of Incidents	16	100

Among the 16 events examined through content analysis, the two criteria with the highest weights are teamwork deficiency and communication deficiency, each with a criterion value of 3.68. These are followed by organizational operation with a criterion value of 2.72, positive safety culture deficiency with a criterion value of 2.4, situational awareness with a criterion value of 2.24, and inadequate supervision and stress/chronic fatigue, each with a criterion value of 0.64. The criterion weight is obtained by multiplying the division of the total number of events by 100 by the percentage weight value.

This value for teamwork;

$$x = \frac{16}{100} \times 23 = 3{,}68$$

The scores and percentage values of the criterion weights obtained from the content analysis are shown in Table 2, Content Analysis Score Table and Figure 18, Content Analysis Score Matrix.

Table 2. Content Analysis Score Table

Factors/Incidents	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	%
Lack of Teamwork	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	15	23
Lack of Communication	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	15	23
Organizational Functioning	●	●	●	●	●		●		●		●		●	●		●	11	17
Lack of Positive Safety Culture	●	●	●	●	●			●		●		●	●		●		10	15
Situational Awareness			●			●	●	●	●	●			●	●		●	9	14
Stress and Chronic Fatigue	●	●	●														3	4
Inadequate Supervision	●					●		●									3	4
Total	6	5	6	4	4	4	4	5	4	4	3	3	4	3	3	4	66	100

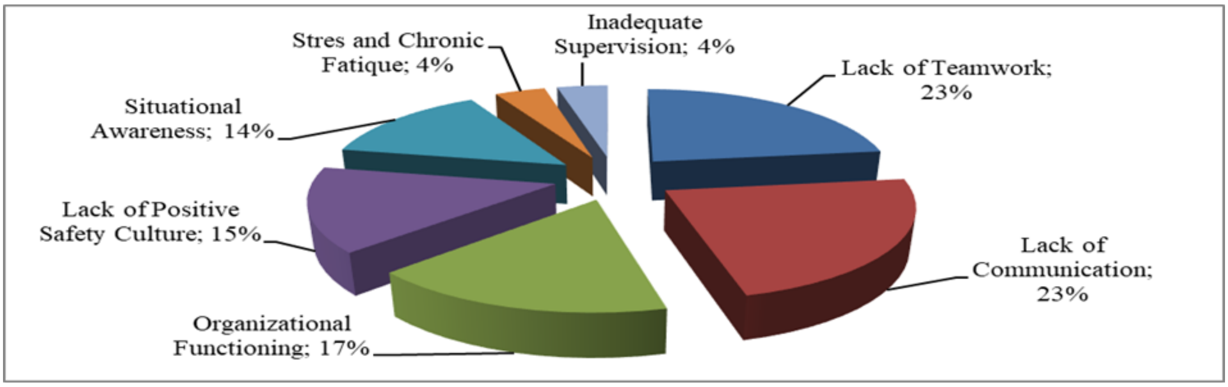

Figure 18. Content Analysis Score Matrix

Among the factors that led to undesirable incidents in the cases examined, the most influential were those stemming from teamwork deficiencies, which accounted for 23%, and communication deficiencies, also at 23%. These were followed by organizational factors/organizational functioning at 17%, lack of a positive safety culture at 15%, situational awareness at 14%, insufficient supervision at 4%, and stress and chronic fatigue at 4%.

According to the content analysis score table, a total of 66 factors were identified as causing the 16 serious incidents, with each incident resulting from more than one factor. Among these, teamwork was a contributing factor in all incidents except for incident 14, and communication deficiency was a contributing factor in all incidents except for incident 13. Organizational functioning was among the factors contributing to 11 incidents; a lack of a positive safety culture contributed to 10 incidents, situational awareness to 9, stress and chronic fatigue to 3, and finally, inadequate supervision contributed to 3 incidents. When examining incidents caused by the most diverse factors, incident 1 occurred due to the influence of all factors except situational awareness, while incident 3 occurred due to the influence of all factors except inadequate supervision. All incidents were caused by more than one factor; the incidents caused by the fewest factors were incident 11, incident 12, incident 14, and incident 15, each of which was limited to being caused by three factors.

4. Conclusion

Among the factors contributing to undesirable aviation incidents identified through content analysis, the relatively higher number of incidents caused by communication and teamwork issues is attributed to the team-based and inter-sector communication nature of air traffic control services. Air traffic control services are carried out by three main sectors: en-route control, approach control, and airport control. These sectors communicate with each other during aircraft handovers. Additionally, the en-route control sector is divided into eastern and western regions, the approach control sector into high altitude and low altitude sectors, and the airport control sector into tower, ground, and clearance delivery sectors. This sectoral division can be further refined in airspaces or airports with higher traffic density. Specifically, in the airport control sector, continuous communication is maintained through both direct verbal interactions between tower and ground control, as well as direct lines with the approach sector, to ensure a smooth traffic flow. The significant 24% impact of teamwork-related factors in undesirable events indicates a vulnerability in this context. Especially in situations where the situational awareness or competence of the controller is low, or when experiencing stress, fatigue, and distraction, teamwork within the team will help reduce the risk of accidents/incidents through effective task distribution. In this context, providing refresher training for air traffic controllers on serious aircraft-to-aircraft and aircraft-to-vehicle near-miss situations, especially in terms of communication and teamwork, will contribute to reducing the risk of accidents/incidents to an acceptable level. Measures to mitigate risks related to communication and teamwork deficiencies can be summarized as follows;

- Providing training on communication between tower and ground controllers will reduce the occurrence of unwanted incidents.
- Establishing local procedures to define the boundaries of communication between tower/approach and tower/ground control will reduce the risk of accidents/incidents. For runway crossings, conducting clearances on the tower frequency instead of relying on verbal communication between tower and ground control will enhance safety.
- Within the framework of teamwork, having supervisors or standby controllers to monitor dense traffic in the operational sectors will help reduce unwanted incidents.
- Within the framework of teamwork, controllers who have experienced similar incidents before serious events and managed to overcome them without major consequences should be temporarily removed from their working positions and allowed to rest according to established local protocols. This approach ensures that they distance themselves from the effects of the incident and are able to think clearly.

Serious aviation incidents resulting from deficiencies in organizational functioning account for 17% of all serious incidents. To reduce such incidents caused by organizational function deficiencies, it is crucial for air traffic controllers to voluntarily report organizational issues within the system. In this regard, the organization should promote a fair culture and avoid a blame culture to encourage controllers to report deficiencies. Identified deficiencies should be addressed through local procedures and implemented by controllers in operations. The measures to mitigate the risks leading to serious incidents due to organizational function deficiencies are as follows;

- The vehicle performing runway inspections should approach the runway from the opposite direction of the active runway, allowing it to see any approaching or departing aircraft.
- Instead of using a handheld radio, the vehicle performing runway inspections should receive clearance through the tower frequency, which is monitored by all aircraft. This will create awareness for both the vehicle driver and the pilots using the frequency, helping to mitigate factors that could lead to runway incursions.
- Although stopbar lights must be used when visibility is below 550 meters, because of runway incursions can occur in any visibility condition keeping the stopbar lights on at taxiway intersections that are not used for departures will create awareness among pilots (ICAO, 2009). This will ensure that even if a controller gives incorrect instructions, any aircraft entering the runway from the opposite direction for taxiing or takeoff will not execute these incorrect instructions.
- Aircraft or towing vehicles that are about to enter the runway should switch to the tower frequency and obtain clearance from the tower controller before starting their entry. This practice will significantly reduce runway incursions.
- As shown in Figure 19, during intersection departures where the angle between the runway in use and the taxiway connecting to the departure runway is less than 90 degrees, it is possible that the pilots of departing traffic may not see the position of the arriving aircraft. This situation poses a risk of unsafe and undesirable events; therefore, intersection departures should not be conducted in such positions.

Figure 19. Runway Intersection Departure in Use

The lack of a positive safety culture (16%), situational awareness (13%), inadequate supervision (5%), and stress and chronic fatigue (2%) should be carefully examined as factors that can lead to serious incidents in the provision of air traffic control services. As with organizational functioning, establishing a reporting culture that is free from a blame culture is crucial for promoting a positive safety culture. Serious incidents that have occurred in the past should be analyzed for their causes in each sector, and these incidents should be communicated to employees through a learning culture. Within the framework of a positive safety culture, organizational and controller-related errors and violations should be reduced. Additionally, controllers' reporting cultures should be supported in incidents that occur, allowing for preventive measures to be taken before more serious incidents happen.

Undesirable incidents in air traffic control services are not only due to air traffic controllers failing to adopt a positive safety culture but also because the organization is unable to activate a safety culture.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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The Effect of Transformational Leadership on Innovative Behaviours of Employees in Aviation Industry. The Role of Trust in the Leader

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Abstract

Transformational leaders are leaders who prioritize harmonizing the valued issues of followers with the values of the organization and thus aim to both increase the success of followers and achieve success goals by ensuring organizational integrity. This study aims to show how the transformational leadership style impacts the innovative behaviours of the aviation industry employees. The study will also attempt to determine the role of trust in the leader in this relationship. Employees of companies offering ground handling services at Ankara Esenboğa Airport provided 252 valid data points with the online survey method prepared in accordance with the model created in the context of the research. Following the analyses employees' innovative behaviours are significantly and positively impacted by transformational leadership, and this link is mediated by the employees' trust in the leader. Inferences and recommendations were made for organisational managers consistent with the data gathered from the study.

1. Introduction

The aviation industry operates in a highly dynamic and competitive environment characterized by rapid technological advancements, fluctuating fuel prices, and ever-changing passenger demands. To thrive in this challenging landscape, organizations within the sector must foster innovation and adaptability. This necessitates a leadership style that encourages creativity, risk-taking, and motivates employees to go beyond their routine duties. Transformational leadership, which inspires and motivates employees to prioritize organizational goals over personal interests, emerges as a critical factor in driving innovative behaviours in this context.

As defined by Bass (1985), transformational leaders go beyond transactional exchanges by inspiring and motivating followers. They articulate a compelling vision, communicate high expectations, and provide individual support and intellectual stimulation to their followers. This leadership style fosters an environment of trust, respect, and psychological safety, enabling employees to think creatively, experiment with new ideas, and contribute to organizational innovation.

When examining the leader-follower relationship through the lens of Social Exchange Theory, the central role of trust becomes evident. This theory posits that individuals exchange resources through social interactions, and these exchanges are built on trust. The leader-follower relationship is a prime example of this. Transformational leaders create a trustworthy environment for their followers, making them feel secure. This sense of security fosters greater commitment to the leader and encourages innovative behaviours. For instance, Avolio and Bass (2004) highlighted the positive correlation between transformational leadership and employee trust, suggesting that trust enhances employees' organizational citizenship behaviours and innovation. More recent studies, such as Zhang et al. (2020), have found that psychological safety strengthens the relationship between transformational leadership and employee innovation. Similarly, Lee et al. (2022) discovered that transformational leadership enhances employees' participation in digital innovation, and this relationship is mediated by psychological safety.

This study aims to investigate the impact of transformational leadership on the innovative behaviours of employees in the aviation industry, particularly those working in ground handling services at Ankara Esenboğa Airport. Given the aviation industry's high safety standards and constantly evolving regulations, the need for innovative solutions is even more pronounced. Therefore, the importance of transformational leadership in this sector is increasingly evident.

This study seeks to answer the following research questions: How does transformational leadership influence the innovative behaviours of employees in the aviation industry? How does trust in leaders, as conceptualized by social exchange theory, shape the relationship between transformational leadership and employee innovation? How do factors such as psychological safety and digital transformation influence the relationship between transformational leadership and employee innovation? Specifically, the study will examine how leader-follower interactions, as viewed through the lens of social exchange theory, impact employee innovative behaviours.

The significance of this study lies in its potential to reveal the role of transformational leadership in fostering innovation among aviation industry employees and the critical role of trust in this process. The findings can guide aviation companies in improving their leadership practices and maximizing the innovation potential of their employees. Additionally, this study contributes to the existing body of knowledge on the relationship between transformational leadership and trust, providing new insights into this field. For instance, Dirks and Ferrin (2002) supported these findings by suggesting that trust increases employees' willingness to take risks and generate new ideas. Similarly, recent studies by Zhang et al. (2020) and Lee et al. (2022) have delved deeper into the relationship between transformational leadership, psychological safety, and innovation.

2. Conceptual Review

2.1. Transformational Leadership

In the last thirty years, the acceptance of Transformational Leadership Theory has significantly increased in the field of organizational leadership. This subject, initially proposed by Burns (1978), has been extensively developed in subsequent studies (e.g., Bass, 1998; Bass & Avolio, 1994). The core of this theory revolves around the leader's ability to enhance the success of their followers. This involves establishing success-oriented goals and inspiring followers to surpass these objectives (Krishnan, 2005).

Transformational leaders prioritize the values held by their followers and strive to assist them in aligning these values with those of the organization. This fosters organizational harmony and facilitates the achievement of organizational goals (Krishnan, 2002). A dynamic relationship characterized by mutual motivation between the leader and followers is a hallmark of transformational leadership, ultimately resulting in shared values and a collective pursuit of higher performance levels (Burns, 1978).

Transformational leaders prioritize emotional intelligence, core values, ethical considerations, established standards, and the pursuit of long-term objectives (Northouse, 2010, p. 171). They are change-oriented and actively encourage innovation and the exploration of new ideas (Bass, 1985). Recent studies have further emphasized the proactive and visionary nature of transformational leaders, highlighting their ability to anticipate and adapt to emerging challenges in dynamic environments (e.g., Avolio & Yammarino, 2019; Zhu et al., 2021).

Transformational leaders exhibit a dynamic and proactive approach. They possess the capacity to motivate both themselves and others to embrace and implement change (Nasir et al., 2020). Research consistently demonstrates a strong correlation between transformational leadership and improved follower behavior and performance (e.g., Antonakis & Day, 2019; Judge & Piccolo, 2004). In this leadership style, the leader empowers followers by actively listening to their innovative ideas and supporting their development (Bass, 1985). Simultaneously, the leader guides the entire process on behalf of the organization by encouraging employees to prioritize business interests over their own (Ergeneli et al., 2007).

In challenging environments characterized by employee dissatisfaction and the need to adapt to environmental demands, a transformational leadership approach is crucial (Bass, 1985, p. 154). Northouse (2010) emphasizes that transformational leaders are uniquely positioned to provide the necessary motivation and empower staff to succeed in uncertain and demanding situations. Recent research has further highlighted the crucial role of transformational leadership in fostering resilience and adaptability in organizations facing complex challenges (e.g., Day & Antonakis, 2016; Sosik & Jung, 2010).

Transformational leadership comprises four key elements: (i) idealized influence, (ii) inspirational motivation aimed at enhancing trust, (iii) intellectual stimulation, and (iv) individualized consideration (Bass, 1990). Idealized influence occurs when the leader fully reflects his sense of duty to his followers, inspiring them to rally around organizational goals (Sabaruddinsah & Asiah, 2022). Inspirational motivation reflects the leader's ability to increase employee motivation by addressing their emotional needs, establishing effective communication, and providing constructive feedback (Rafferty & Griffin, 2004). This aspect ensures that employees strive to achieve desired performance levels by adapting and developing their current behaviors. Individualized consideration emphasizes the leader's understanding of individual employee needs and tailoring development activities accordingly (Yukl, 1999). Intellectual stimulation focuses on two key aspects: ensuring employee compliance and encouraging them to embrace innovation (Bednall et al., 2018).

Research indicates that transformational leadership significantly influences follower satisfaction, emotional commitment to the organization, and job performance (Koh et al., 1995; Jiatong et al., 2022). Furthermore, it has been established that transformational leadership plays a crucial role in shaping employees' attitudes towards organizational change (Yu et al., 2002) and the overall organizational climate (Lam et al., 2002). Additionally, findings suggest that transformational leadership impacts innovation, work stressors, creativity (Nasir, 2022), organizational culture (Koç, 2024), job motivation, job satisfaction, and performance (Anindita & Tanuwijaya, 2023; Xu & Wang, 2008). Recent studies have further demonstrated the positive impact of transformational leadership on organizational agility, resilience, and long-term sustainability (e.g., Luthans & Avolio, 2004; Sivasankaran et al., 2020). Transformational leadership is essential in all organizations due to its significant influence on both individual and organizational outcomes (Tucker & Russell, 2004).

In summary, transformational leaders work to ensure that employees align with the organization's goals and values (Hickman, 1997, p. 9). They build commitment to a common purpose by fostering trust among followers and possess the capacity to inspire and energize their subordinates through their behaviors (Bass et al., 1987).

2.2. Innovative Behaviors

Innovative behaviors encompass a range of employee actions that contribute to the development and implementation of new ideas and practices within an organization (West & Farr, 1990). These behaviors go beyond routine tasks and involve actively seeking out and implementing novel solutions to challenges (Gülbahar, 2019).

Research has consistently demonstrated a strong link between innovative behaviors and organizational success (e.g., Amabile, 1997; Janssen, 2000). For instance, Amabile (1997) emphasized the crucial role of employee creativity and innovation in driving organizational competitiveness and adaptability.

Innovative behaviors are multidimensional and include aspects such as identifying opportunities, generating new ideas, promoting those ideas, and successfully implementing them (Scott & Bruce, 1994; Kleysen & Street, 2001; De Jong & Den Hartog, 2010). These behaviors span the entire innovation process, from the initial conceptualization of a new idea to its successful implementation and integration into organizational practices.

The impact of innovative behaviors extends beyond individual contributions and significantly influences organizational performance. For example, Janssen (2000) found that employee innovation is positively associated with organizational effectiveness, including increased productivity, improved quality, and enhanced market share. More recent studies have further emphasized the critical role of employee innovation in driving organizational agility, adaptability, and long-term sustainability (e.g., Ireland et al., 2015; Zahra & George, 2002).

Research has also explored the antecedents of innovative behaviors, identifying both individual and organizational factors as key drivers. Individual factors include self-efficacy, a propensity to question established norms, and external professional connections (Blackman & Chan, 2016). Organizational factors such as strong leadership, a supportive organizational culture, and adequate resources have been consistently shown to foster employee innovation (e.g., Amabile & Kramer, 2007; Janssen, 2000).

Furthermore, research has investigated the interplay between innovative behaviors and other organizational outcomes. For example, Janssen et al. (2004) demonstrated that while employee innovation can lead to positive outcomes such as enhanced performance and improved work attitudes, it can also have negative consequences, such as increased stress and conflict. More recent studies have explored the mediating role of innovative behaviors in various organizational contexts. For instance, Ordu & Sarı (2022) found that innovative behaviors mediate the relationship between organizational support and employee well-being. Hock-Doepgen et al. (2024) demonstrated a positive relationship between innovative behaviors and organizational support, while Pigola et al. (2023) highlighted the positive impact of innovative behaviors on innovation performance.

In conclusion, innovative behaviors play a crucial role in organizational success and are influenced by a complex interplay of individual, team, and organizational factors. Understanding the antecedents and consequences of these behaviors is critical for organizations seeking to foster a culture of innovation and achieve sustainable competitive advantage.

2.3. Trust in the Leader

Trust refers to the degree of confidence one has in the reliability of an individual's statements, behaviours, and choices to whom it is directed, which occurs between two people and determines the quality of the mutual relationship. This perception affects whether or not to agree with the words or decisions of the other party in the individual relationship process, and whether or not to comply with these decisions and statements (McAllister, 1995).

Research typically evaluates various dimensions, including talent, benevolence, honesty, and predictability (Dietz & Den Hartog, 2006). Leadership is a type of relationship where the quality of mutual relationships is expected to be at the highest level. The relationship of trust between leaders and their followers is closely linked to the followers' confidence in the leader's decisions and behaviours and the expectation that these decisions will manage the relevant event positively (Schoorman et al., 2007).

For leaders, the bonds and connections they have with their followers are essential to ensure their own dominance over work behaviours (Farmanesh & Zargar, 2021). In this context, the dynamic between the leader and the followers holds significant importance. Trust evolves gradually throughout this process and is influenced by the nature of the process itself. Followers examine the leader's behaviour towards them and allow the development of trust with criteria such as being honest and fair in relations with others (Dirks & Ferrin, 2002).The leader occupies a pivotal position within the framework of organizational operations and is expected to gather and direct employees around organizational goals. That's why trust in the leader is expected to be the basic element in managing this relationship (Fairholm, 1994). The leader is not only a role but also the communication and interaction point between the organization's employees and the upper management (Bennis, 2007).

Since trust creates positive feelings in employees and increases interest in work, experiencing trust may result in behaviours that extend beyond formal job responsibilities, foster voluntary intentions, enhance participation, and contribute to increased job satisfaction and performance levels. There are some studies on this subject and it has been revealed that the reason for the failure of many businesses is the lack of trust in the leader (Gompers & Metrick, 2001). Similarly, it has been suggested that the underlying reason for success stories is related to the level of trust (McLain & Hackman, 1999). The best way to demonstrate this relationship is to emphasize the two-way trust, positive feelings and respect between the leader and the followers in the Leader-Member Exchange Theory (Dansereau et al., 1975).

A reliable institutional environment and organizational climate increases the quality of all relationships and brings about a high level of cooperation (Käser & Miles, 2002). Trust in leadership primarily feeds the performance required for organizational performance (Dirks, 2000). The most important requirement manifests itself in processes related to issues that employees are generally reluctant to, such as innovative behaviors. Trust in the leader causes these processes to be more constructive and even to initiate these processes. The leader reduces the reluctance or fear of employees at the level of trust in him/her. For this reason, it is necessary for leaders to establish reliable relationships in environments where innovative behaviors are desired to be triggered (Judge, et al., 2006). As a result, it has been stated that a strong degree of trust fosters collaboration and enhances overall performance (Ghilic-Micu & Stoica, 2003). In this respect, it is advantageous for leaders to cultivate a strong foundation oftrust in their relationships with their followers. In this respect, trust is considered as an important variable in this study.

2.4. Developing Hypotesis

Research suggests that confidence in leadership may serve as a mediating factor between transformational leadership and innovative behaviors within the context of organizational innovation. The process of innovation presents significant challenges, and preparing for this process may not always be at the desired level. Sometimes employees may not believe in the necessity of innovations to be made. In fact, breaking away from work routine may seem like a difficult and unnecessary obligation for them (Gülbahar et al., 2023; Gülbahar & Karadal, 2022). This lack of confidence can hinder employee engagement in innovative activities and limit their willingness to take risks and embrace new ideas (Dirks & Ferrin, 2002; Mayer et al., 1995).

At this point, the connection between the leader and the trust established by the followers can cause them to accept this idea quickly, to be convinced that they will receive sufficient guidance, and sometimes even to initiate innovation movements willingly and without any demand or pressure from the management. Here we propose:

H1. Transformational leadership exerts a positive and significant influence on the trust in leaders.

During periods of organizational change or other situations requiring innovation, when employees initiate innovation activities, are involved in the process and trigger different innovation processes, the organizational climate, the organization's support for employees and, most importantly, the trust in leaders either prevent or accelerate these activities, providing a positive effect on organizational outputs.

Innovation processes are quite painful and difficult processes. Although it is always expected that employees will accept the innovation, implement it, and even be eager for the next innovation at an optimal level, in reality, employees may not be so eager or talented. Sometimes, even if they have sufficient skills for this, they may need a triggering force to start this process. Within the realms of organizational transformation and innovative strategies, the cornerstone of trust inspires employees to feel driven, enabled, engaged in the transformation journey, and introduce fresh changes to the organization (Käser & Miles, 2002). From this we put forward:

H2. Trust in leader has a positive and significant effect on innovative behaviours.

Research suggests that trust in leadership can contribute to the mobilization of innovative ideas during periods of change (Li et al., 2019). The connection between trust in leadership and innovative actions can be interpreted through the lens of ***Social Exchange Theory***, which posits that interpersonal relationships, including those between leaders and followers, involve an exchange of resources and benefits (Homans, 1958). When employees trust their leaders, they are more likely to perceive that their contributions will be valued, feel comfortable taking risks, and be willing to invest their time and effort in organizational goals. This trust-based exchange fosters a positive and mutually beneficial relationship, creating a conducive environment for innovation.

Transformational leaders, by inspiring and motivating their followers, enhance trust in leadership. This trust, in turn, encourages employees to engage in innovative behaviors.

H3. Followers' trust in the leader plays a mediating role in the relationship between transformational leadership and innovative behaviors.

This hypothesis proposes that the positive impact of transformational leadership on employee innovation is mediated by the level of trust followers have in their leader. In other words, transformational leadership indirectly influences employee innovation by increasing trust in the leader, which in turn motivates employees to engage in innovative behaviors.

3. Research Method

3.1. Participants

The connection between TP and innovative behaviors was investigated in the research. It also investigated the role of trust in the leader in this relationship. The study was carried out with data collected from employees working in the aviation sector. It was carried out with employees of companies providing ground handling services at Ankara Esenboğa Airport. Data were collected electronically from employees of 3 companies providing airport services and valid data was obtained from 252 employees (8 invalid data and n=1362). The sample size of 252 participants is considered sufficient for this study, as it meets the recommended sample size for structural equation modeling (SEM) analyses, which typically requires a sample size of at least 200 participants for adequate statistical power (Hair et al., 2019). The questionnaire aimed at the respondents was structured with an initial part featuring demographic inquiries and a subsequent segment containing the measured variables relevant to the study. The descriptive information of the participants is as follows:

The respondents participating in the survey are predominantly female employees (64.3% female and 35.7% male). Likewise, the rate of single people is higher than the rate of married people (61.7% of the participants are single, 38.3% married).In the age range, the most dominant age group is 26-35 (39.3%, others are 18-25 years old 14.8%, 36-45 years old 26.1%, 46 and above 19.8%), while the majority of the education is 4-year university graduates (36.5%, others are 14.3% high school, 40.4% associate degree, 8.3% postgraduate). The technical class they work in is determined as 22.1% representation, 6.3% passenger traffic, 27.2% load control and communication, 12.4% ramp, cargo, mail, aircraft cleaning, uld control, 9% surveillance and management services, 2% flight operation and 21% transportation. Finally, in terms of seniority, 1-3 years was evaluated as 15.1%, 4-6 years as 10.1%, 7-9 years as 20.9%, 10-15 years as 27.2% and 16 years and above as 26.7%.

3.2. Measures

Innovative Behaviour Scale: The scale developed by Scott and Bruce (1994) was used. Responses were taken on a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). The scale is as a single dimension and a 6-item scale.

Trust in Leader Scale: Employees' trust in their leader was measured using a seven-item scale developed by Robinson, S.L. & Rousseau, D.M. (1994). One sample item included, "I believe my leader has high integrity". Items 2-5-6 in the scale were used as reverse items.

Transformational Leadership Scale: The assessment of TP was conducted using a scale with four-items developed by McColl-Kennedy and Anderson (2002).

4. Findings

The data analyses for this research were performed using SPSS 25.0 and AMOS 24.0 software tools. The SPSS software facilitated descriptive statistics and correlation analyses, whereas the AMOS software was employed for assessing reliability and validity of the constructs and testing hypotheses.

4.1. Data Analysis

Table 1 includes the mean, standard deviation and correlation values of the variables. According to the correlation analysis results, a positive and significant relationship was found between TP and trust in the leader (r=0.32; p<0.01). Similarly, a positive and significant relationship was found between trust in the leader and innovative behaviours (r=0.61; p<0.01).

Table 1. Mean, Standard Deviation and Correlation Values

Constructs	M	SD	1	2	3
1. TRL	4.09	0.88	1		
2. TL	3.86	1.05	0.32**	1	
3. IB	4.01	0.93	0.40**	0.61**	1

Notes: n=252; **p<0.01; M=Mean; SD=Standard Deviation; TRL=Transformational Leadership; TL=Trust in Leader; IB=Innovative Behaviour

4.1.1. Measurement Model

The research tested the measurement model with confirmatory factor analysis (CFA) using the AMOS software. In this scenario, the maximum likelihood approach was employed to determine if the expected configurations of the scales were consistent with the data gathered (Jöreskog & Sörbom, 2006).

The measurement model to the provided data was evaluated based on the fit indices recommended by Hu and Bentler (1999). These are; chi-square (χ^2), degrees of freedom (df), root mean square error of approximation (RMSEA), standardized root mean square residual (SRMR), goodness of fit index (GFI) and comparative fit index (CFI). Of these indices, a $\chi 2$/df value below 3, RMSEA and SRMR values below 0.05, and GFI and CFI values above 0.95 is an indication that the model has a high goodness of fit (Byrne, 2016; Kline, 2016). As a result of the CFA, χ^2/df=1.60; RMSEA=0.04; SRMR=0.03; GFI=0.92; CFI=0.98 was determined and it was observed that the specified criteria for the indices were met.

In the study, after structural validity analysis, reliability, convergent and discriminant validity were tested. Internal consistency reliability is provided by Cronbach's alpha (α) and composite reliability (CR) being > 0.70. For convergent validity, standardized factor loadings > 0.50; CR > 0.70; average variance extracted (AVE) > 0.50; CR > AVE, and for discriminant validity, AVE > maximum shared variance (MSV); AVE > average squared variance (ASV) are accepted (Hair et al., 2014).

These values are presented in Table 2 and α and CR values were found to be > 0.70 (Nunnally, 1978). The results show that standardized factor loadings are >0.50, CR is 0.70, AVE is 0.50, CR values for each factor are higher than AVE, and AVE values are also higher than MSV and ASV, and thus within the recommended ranges. (Hair et al., 2014; Malhotra & Dash, 2011). These data indicate that the model has sufficient structural validity, internal consistency reliability, convergent and discriminant validity.

Table 2. Measurement Model

Constructs	Items	Factor Loadings	α	CR	AVE	MSV	ASV
Transformational Leadership	TRL1	0.77**	0.88	0.88	0.66	0.18	0.15
	TRL2	0.87***					
	TRL3	0.80***					
	TRL4	0.79***					
Trust in Leader	TL1	0.89**	0.94	0.93	0.67	0.41	0.26
	TL2	0.69***					
	TL3	0.87***					
	TL4	0.85***					
	TL5	0.79***					
	TL6	0.78***					
	TL7	0.85***					
Innovative Behaviour	IB1	0.69**	0.93	0.94	0.74	0.41	0.30
	IB2	0.88***					
	IB3	0.91***					
	IB4	0.85***					
	IB5	0.90***					
	IB6	0.90***					

Notes:***p<0.001; **p<0.05 α=Cronbach's Alpha; CR=Composite Reliability; AVE=Average Variance Extracted; MSV=Maximum Squared Variance; ASV=Average Shared Square Variance

4.1.2. Structural Model

This study employed a structural model analysis with 5,000 bootstraps and calculated a 95% confidence interval (CI) to determine the upper and lower boundaries, which aids in comprehending the significance level. The results of the hypothesis test are displayed in Table 3. TP explains 14% (R^2) of the change in trust in leader, while trust in leader explains 43% (R2) of the change in innovative behaviour.

According to the findings, TP has a positive significant effect on trust in leader (β=0.37; p<0.001). Therefore, hypothesis 1 is supported. Trust in leader has a positive significant effect on innovative behaviour (β=0.66; p<0.001). According to this result, hypothesis 2 is also accepted.

Upon examining the bootstrap results, it is seen that the indirect effect of TP on innovative behaviour through trust in leader is significant (β=0.24; p<0.001). This finding supports hypothesis 3.

Table 3. Results of Hypothesis Testing

Hypotheses	Paths	β	p	CI	Result
H1	TRL → TL	0.37	0.001***	(0.195–0.519)	Supported
H2	TL → IB	0.66	0.001***	(0.551–0.745)	Supported
H3	TRL → TL → IB	0.24	0.001***	(0.121–0.366)	Supported

Notes: ***p<0.001; Coefficients are standardized (β); TRL=Transformational Leadership; TL=Trust in Leader; IB=Innovative Behaviour

5. Discussion

This study investigated the influence of Transformational Leadership on employee innovative behaviors within the aviation sector, specifically focusing on ground handling services. The findings provide valuable insights into the critical role of trust in leadership as a mediator in this relationship.

The study's findings align with previous research that has consistently demonstrated a positive relationship between transformational leadership and employee innovation (e.g., Zhu et al., 2021; Wang & Zhang, 2022; Wang & Zhang, 2023). These studies have shown that transformational leaders, through their inspiring and motivating behaviors, can significantly enhance employee engagement in innovative activities.

Furthermore, the finding that trust in leadership mediates the relationship between transformational leadership and employee innovation is consistent with existing literature (e.g., Dirks & Ferrin, 2002; Mayer et al., 1995). These studies have highlighted the crucial role of trust in facilitating the exchange of information and resources between leaders and followers, which is essential for fostering innovation. This finding is also supported by Rousseau (1995) who argues that trust is a cornerstone of psychological contracts, which govern the exchange relationships between individuals in organizations. In the context of this study, the findings suggest that when employees trust their transformational leaders, they are more likely to perceive a fair and equitable exchange relationship, leading to increased engagement in innovative behaviors.

5.1. Implications

Theoretical Implications:

This study contributes to the existing body of knowledge on transformational leadership by providing empirical evidence for the mediating role of trust in leadership within the context of employee innovation within the aviation sector. These findings further strengthen the understanding of the complex interplay between leadership styles, trust, and employee behaviors.

Practical Implications:

- ***For Aviation Industry Leaders:*** The findings emphasize the importance of cultivating trust among employees. Leaders should strive to build strong and authentic relationships with their teams, communicate openly and honestly, and demonstrate genuine concern for employee well-being. This can be achieved through active listening, providing regular feedback, and empowering employees to take ownership of their work.
- ***For Human Resource Management:*** Human Resource departments can play a crucial role in fostering trust by implementing initiatives that enhance employee engagement, provide opportunities for professional development, and create a supportive and inclusive work environment. These initiatives may include employee recognition programs, mentorship programs, and team-building activities.

5.2. Limitations and Future Research Directions

This study, while providing valuable insights, has some limitations. Firstly, the study was conducted within a specific sector (aviation) and focused on a particular employee group (ground handling services). Future research should investigate the generalizability of these findings to other sectors and employee populations. For instance, research could explore the relationship between transformational leadership, trust, and innovation in other industries such as healthcare, technology, and manufacturing.

Secondly, the study relied on cross-sectional data, which limits the ability to establish causal relationships. Longitudinal studies are needed to further investigate the temporal dynamics between transformational leadership, trust in leadership, and employee innovation. By collecting data over time, researchers can better understand the evolution of these relationships and identify the direction of causality.

Thirdly, the study focused on a limited set of variables. Future research could explore the moderating effects of other factors, such as organizational culture, employee demographics, and industry dynamics, on the relationship between transformational leadership, trust, and innovation. For example, research could investigate how organizational culture, characterized by factors such as openness to change and employee empowerment, may moderate the impact of transformational leadership on employee innovation.

6. Conclusion

This study provides valuable insights into the critical role of transformational leadership and trust in fostering employee innovation within the aviation sector. The findings emphasize the importance of cultivating trust among employees as a key strategy for enhancing innovation.

The study's findings have important implications for leaders, human resource managers, and organizations seeking to enhance their innovative capabilities. By fostering a culture of trust and empowering employees, organizations can create an environment that encourages creativity, innovation, and ultimately, organizational success.

Ethical approval

Approval for this research was authorized by the Science and Engineering Research Ethics Committee (Nevşehir Hacı Bektaş Veli University) under decision number 2024.09.214, dated September 27, 2024.

Conflicts of Interest

The authors declare that there are no conflicting interests associated with the publication of this document.

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The Impact of Geodemographic Factors on Airport Traffic in Türkiye: An Aviation Analysis

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Abstract

This study examines the relationship between passenger volumes at Turkish airports and the demographic and geodemographic characteristics of the provinces in which they are located. By analyzing data on passenger traffic, cargo traffic, and aircraft movements, the research highlights how population size, economic activity, and tourism shape airport traffic patterns. The findings indicate that tourist-heavy regions, such as Antalya and Muğla, experience significant seasonal spikes driven by summer tourism, while industrial hubs like Istanbul and Izmir exhibit consistent cargo traffic linked to economic activity. Larger, economically active cities tend to have higher levels of aircraft movements, reflecting the dual impact of business and population density. These results emphasize the need for tailored airport planning strategies, including enhanced infrastructure in tourist regions and improved logistics capabilities in economic centers. The study underscores the importance of incorporating geodemographic factors into aviation planning to promote regional connectivity and support economic growth.

1. Introduction

The airline industry represents a cornerstone of the global transportation network, playing a vital role in fostering connections between people, cultures, and economies. This multifaceted sector encompasses commercial aviation, cargo transport, airport operations, and airline management, all operating within a highly complex and competitive environment. External factors, such as economic fluctuations, technological advancements, and geopolitical events, significantly shape the industry's dynamics. Equally critical, internal factors—such as organizational structure, corporate culture (Riwo-Abudho et al., 2013), and marketing communication strategies (Koçak, 2022; Koçak et al., 2024)—further influence aviation performance and operational outcomes. Moreover, consumer behavior, including search behaviors (Koçak, 2023; Doğan et. al, 2018), plays a pivotal role in shaping demand and preferences within the aviation market. Together, these external and internal drivers underscore the need for adaptive strategies that align with the evolving demands of both global and regional markets (Yadav & Goriet, 2022).

Additionally, technological advancements such as improvements in aircraft fuel efficiency and the adoption of digital innovations have reshaped industry practices, allowing airlines to reduce operational costs and enhance passenger experiences (Sun et al., 2021). However, the airline industry remains highly susceptible to disruptions from geopolitical events such as conflicts, economic sanctions and pandemics, which can cause significant declines in passenger demand and changes in traffic flow patterns (Fu et al., 2009).

Furthermore, air transport liberalization and globalization have spurred increased competition and connectivity, allowing airlines to expand their networks across borders, which has resulted in greater efficiency and economic growth globally (Grančay, 2010). Yet, this expansion also brings challenges related to environmental sustainability, as the growth of air traffic continues to exacerbate its impact on climate change (Budd et al., 2019).

This dynamic and ever-evolving industry requires continuous adaptation to external pressures and opportunities, making strategic planning crucial for maintaining competitiveness in a globalized and interconnected world.

The influence of geodemographic factors on aviation, particularly in terms of air travel patterns, is a critical area of research that uncovers the profound interplay between urbanization, age distribution, and income levels. Significant insights have been derived from various studies, emphasizing how these elements shape air travel trends.

Urban centers with high population densities are foundational in generating air passenger traffic. Notably, a study examining U.S. air transportation highlighted a direct correlation between urban population distribution and air passenger traffic, revealing the substantial impact of urban size and geographical proximity to other urban centers on air travel patterns (Taaffe, 1956).

Additionally, the age composition within a population markedly influences travel preferences. Younger individuals tend to travel more frequently for business, whereas older demographics might favor leisure travel. Insights from smart card data in urban transit systems demonstrate how age-specific travel behaviors resonate within air travel dynamics, providing relevant implications for the aviation sector (Zhang et al., 2020).

Income levels also play a decisive role in air travel frequency and route demand. Studies indicate that individuals with higher incomes are more likely to engage in air travel, both domestically and internationally. This pattern extends to private air travel, where higher-income groups exhibit increased frequency, particularly for private purposes, influencing overall aviation trends (Bruderer Enzler, 2017).

The process of urbanization not only boosts demand for air travel but also critically influences the development of air travel infrastructure. Research indicates that cities experiencing rapid urban growth, especially those expanding into dense hubs, become central to airline routes and networks. This urbanization effect is pivotal in shaping long-haul travel routes and the density of air traffic, with major global hubs such as New York, London, and Singapore exemplifying this trend (Matsumoto, 2007).

Geodemography, as a complex field, enhances the understanding of social segmentation and serves as a valuable tool in marketing. Geodemographic profiling and analysis have been regarded by many marketers as a means to move beyond the constraints of traditional class-based population categorizations. Furthermore, geodemographic systems have enabled the implementation of targeted promotional strategies, as opposed to mass marketing approaches. Overall, such methods have been widely embraced and adopted with enthusiasm within the marketing domain (Sivadas, 1997). Geodemographic factors like population density, income, and urbanization strongly influence aviation patterns by shaping demand, route planning, and air traffic distribution. As cities continue to urbanize and populations grow wealthier, these factors will further intensify the need for efficient air transport solutions.

The aviation sector significantly contributes to Türkiye's economy, especially through its support of the tourism industry, a major component of the national GDP. The prominence of Turkish Airlines as a global carrier and the development of major infrastructures like Istanbul Airport have enhanced international connectivity, thereby facilitated trade and tourism and generated substantial employment (Cecen et al., 1994). Technological progress in the sector has been centered on the adoption of modern, fuel-efficient aircraft and the integration of digital tools to boost operational efficiency. Significant investments have been made in modernizing fleets with aircraft like the Boeing 787 and Airbus A350, alongside incorporating technologies for real-time data analytics and predictive maintenance, which streamline operations (Sun et al., 2021).

Turkiye’s strategic geographical location at the intersection of Europe, Asia and the Middle East makes it a critical regional hub for air travel and trade. Its proximity to major global markets and its role as a transit point for both east-west and north-south routes enhance its importance in the aviation sector. Turkey has also developed a robust aviation infrastructure, exemplified by major international airports such as Istanbul Airport, which serve as a major connector for long-haul and regional flights. This context highlights the importance of analyzing passenger traffic and demographic trends in Turkey, given its significant role in facilitating global connectivity (iata.org, 2024).

In recent years, sustainability has become a critical focus, with Turkish airlines and airports implementing various initiatives aimed at reducing carbon emissions. These measures include using biofuels, optimizing flight routes, introducing electric ground vehicles, and exploring sustainable aviation fuels to minimize environmental impact (Budd et al., 2019). However, the industry faces challenges such as economic fluctuations, geopolitical tensions, and regulatory issues. Despite these obstacles, Türkiye's strategic geographical positioning as a global hub offers numerous growth opportunities, particularly with the ongoing expansion of Turkish Airlines and the development of major airports (Nalçacigil & Kacar, 2022). Looking forward, the Turkish aviation industry is poised to adapt to shifts in passenger preferences towards sustainable travel and innovate further in the digital realm, including the utilization of AI for customer service and operational enhancements. The post-pandemic recovery, coupled with increasing regional and international travel demand, suggests that Türkiye will maintain its significant stature in the global aviation market (Ryley, 2017).

The airline industry plays a central role in global connectivity, enabling the movement of people and goods across regions. Understanding air traffic patterns requires integrating geodemographic analysis to explore the interplay between geographic, demographic, and economic factors. This study aims to examine the influence of population density, urbanization, and economic activities on air traffic in Türkiye, providing localized insights into airport traffic patterns. By emphasizing geodemographic analysis, this research fills gaps in existing literature, shifting from broad national trends to specific regional impacts. The findings contribute to understanding how demographic factors shape airport planning and policy development.

The literature demonstrates that the number of passengers at Turkish airports is heavily influenced by demographic factors like population density, income levels, and proximity to urban centers. Larger airports in metropolitan areas like Istanbul, Ankara, and Antalya see the highest passenger volumes and efficiency levels. This relationship highlights the importance of socioeconomic development, regional planning, and airport accessibility.

Despite these valuable insights, there are gaps in the literature, particularly in understanding how specific demographic changes, such as internal migration and regional economic disparities, influence airport passenger numbers. Existing research tends to focus on broad national trends, often overlooking the nuances of how individual provinces' demographic profiles shape air travel demand. This study aims to address this gap by offering a detailed analysis of how provincial demographic and geodemographic factors directly impact airport passenger numbers.

Table 1. Previous Studies

Study	Main Objective	Methodology	Key Findings	Conclusions
Albayrak et al. (2020)	Analyze air traffic determinants in Türkiye	Provincial-level analysis	Population and GDP positively influence air passenger traffic	Socioeconomic factors are crucial in planning new airports
Kim & Yoon (2021)	Impact of geodemographics on urban air mobility	Spatial analysis	Urban space and population density influence air transport planning	Geodemographic data helps improve urban mobility strategies
Dziedzic et al. (2020)	Study air traffic volumes at small EU airports	Regression analysis	Population size and airport charges are significant factors	Regional dynamics influence small airport passenger flows
Paköz & Sakarya (2021)	Evaluate spatial accessibility changes to airports	Spatial accessibility analysis	Recent airport developments increased accessibility in the east	Major hubs still dominate air traffic
Erdem et al. (2020)	Examine topology of Turkish air transport network	Network analysis	Population centers like Istanbul dominate the network	High population areas shrink travel distances
Yaylali et al. (2016)	Analyze airline choice behavior	Logit models	Demographic factors impact airline choice	Socioeconomic profiles shape travel behaviors
Koçak (2011)	Measure efficiency of Turkish airports	DEA	Larger airports are more efficient due to location in vibrant regions	Efficiency tied to regional economic activity
Gunter & Zekan (2021)	Forecast global air passenger demand	GVAR model	Connectivity and economic factors drive air passenger demand	Global networks significantly impact airport traffic
Leung et al. (2017)	Analyze geo-demographics in passenger preferences	Geo-demographic classification	Geographic targeting can increase low-cost carrier traffic	Geodemographics are crucial for marketing strategies
Calisir et al. (2016)	Study factors affecting passenger loyalty	Structural equation modeling	Service quality affects loyalty more than price	High service quality leads to higher passenger retention

This study is organized into four main sections. Following the introduction, the Materials and Methods section details the data collection process, the tools and techniques employed, and the methodological framework for analyzing geodemographic factors and airport traffic patterns. The Results and Discussions section presents the key findings, emphasizing the influence of population size, economic activity, and tourism on passenger volumes, cargo traffic, and aircraft movements, along with their implications for airport management. The Conclusion section summarizes the primary outcomes of the research, highlights its contributions to the literature, and offers actionable recommendations for policymakers and planners. Lastly, limitations of the study and suggestions for future research are outlined to guide further exploration of geodemographic influences on aviation.

2. Materials and Methods

This study employs a geodemographic approach, analyzing datasets from the Turkish Statistical Institute (TUIK) and the General Directorate of State Airports Authority. Monthly data on passenger numbers, cargo traffic, and aircraft movements from January to September were analyzed using Python libraries for data transformation and visualization. Correlation analysis, employing Pearson coefficients, was conducted to assess the relationship between population size and air traffic metrics. The methodology emphasizes identifying trends and disparities influenced by geodemographic factors

2.1. Data Collection

Data concerning the number of passengers, volumes of cargo, and aircraft movements are accessible through the official website of the Ministry of Transport and Infrastructure of the Republic of Türkiye, specifically the General Directorate of State Airports Authority.These datasets have been meticulously compiled on a monthly basis for the period from January to September. The data encompass three principal categories of airport traffic:

Passenger Traffic: This category captures the total number of passengers handled by the airports, providing insights into the flow of individuals through these transportation hubs.

Cargo Traffic: This includes detailed records of the cargo handled by the airports, which is indicative of economic activity and logistical capacity.

Aircraft Movements: This measures the total number of aircraft takeoffs and landings, offering a metric of airport operational intensity.

Additionally, demographic and population statistics for the provinces where these airports sourced from the Turkish Statistical Institute (TUIK, 2024). These datasets were methodically organized into Excel spreadsheets to facilitate a comprehensive analysis. Each sheet provides granular details on monthly traffic metrics for major Turkish airports. This compilation of data supports the execution of a correlation analysis aimed at exploring the relationships between the size of the population in each city and the corresponding airport traffic volumes, thereby contributing to a deeper understanding of regional air transport dynamics within Türkiye.

2.2. Data Processing

The data processing phase leveraged Python's Pandas library, which was employed for efficient data cleaning, transformation, and analysis. Descriptive statistical analyses were conducted to explore traffic patterns and identify trends within the datasets. To visualize these patterns, line graphs were generated to depict month-to-month variations, highlighting seasonal fluctuations in passenger, cargo, and aircraft movements. These visualizations provided clear insights into how traffic evolved over the months, enabling the identification of peak and trough periods for each category of traffic.

2.3. Geodemographic Analysis

This study also incorporated a geodemographic analysis to examine the effects of geographic location, city size, and economic characteristics on airport traffic. Specifically, the relationship between population size and each traffic category was explored in the context of regional economic activity, tourism, and industrial outputs. Geodemographic factors were considered critical to understanding the distinct traffic patterns at different airports, especially in tourism-dominated versus industrial regions.

2.4. Correlation Analysis

Pearson correlation coefficients were computed to measure the strength and direction of the relationship between population size and the three traffic types:

- **Passenger Traffic**
- **Cargo Traffic**
- **Aircraft Movements**

The correlation analysis provided quantitative insights into the degree to which population size influences each form of airport activity, offering a nuanced understanding of geodemographic impacts.

2.5. Limitations of the Study

This study is subject to several limitations that should be considered when interpreting the findings:

Limited Dataset: The dataset used in this study only covered a nine-month period, which may not fully capture seasonal fluctuations or the impact of one-off events such as economic shocks or natural disasters.

Exclusion of Income and Other Socio-Economic Data: While population size was used as a proxy for demographic characteristics, other relevant socio-economic factors, such as disposable income, education levels, and regional migration patterns, were not included in this analysis. Future studies should integrate these variables to provide a more nuanced understanding of the determinants of air traffic demand.

Focus on Passenger and Cargo Traffic: Although the study included aircraft movements, it did not delve into the operational efficiency of airports or the impact of infrastructure limitations on traffic volumes. Future research could incorporate an analysis of airport efficiency metrics to better understand the operational challenges faced by Turkish airports

3. Results and Discussions

Findings reveal the following:

Passenger Traffic: Coastal airports like Antalya show seasonal peaks due to tourism, while urban hubs like Istanbul demonstrate consistent activity linked to economic drivers.

Cargo Traffic: Istanbul leads in cargo volume due to its economic prominence, while regional cities reflect steady growth tied to industrial activities.

Aircraft Movements: Trends mirror passenger traffic, with tourism-heavy airports showing seasonal spikes and business-centric airports maintaining stable operations.

The correlation analysis highlights a moderate relationship (0.316) between population size and passenger traffic, driven significantly by tourism, while stronger correlations (0.486 for cargo and 0.562 for aircraft movements) underscore the role of economic activity and urban density.

3.1. Passenger Traffic Trend Analysis

The data in Table 2 reveals strong tourism patterns in Türkiye, particularly highlighting seasonality at coastal airports like Antalya and Muğla Dalaman, which experience sharp summer spikes, indicating a reliance on seasonal tourism. In contrast, central airports such as Istanbul Sabiha Gökçen, Izmir, and Ankara Esenboğa show steadier growth, though they also peak moderately in summer. Table 2 shows that July and August are the highest traffic months across all airports, aligned with peak summer travel, while September brings a slight decline, marking the end of the travel season. These trends underscore Türkiye's dual appeal as both a year-round destination in urban centers and a seasonal hotspot in coastal areas

Table 2. Outlines the monthly passenger traffic for five major Turkish airports.

Month	Istanbul Sabiha Gökçen	Ankara Esenboğa	Antalya	Izmir	Muğla Dalaman
January	2.001.000	928.000	700.000	605.000	200.000
February	2.050.000	945.000	730.000	610.000	210.000
March	2.300.000	1.010.000	900.000	660.000	250.000
April	2.400.000	1.050.000	1.400.000	700.000	600.000
May	2.800.000	1.200.000	2.000.000	900.000	1.000.000
June	3.100.000	1.350.000	2.500.000	1.000.000	1.500.000
July	3.500.000	1.400.000	2.800.000	1.100.000	1.700.000
August	3.600.000	1.450.000	2.900.000	1.200.000	1.800.000
September	3.400.000	1.400.000	2.600.000	1.150.000	1.600.000

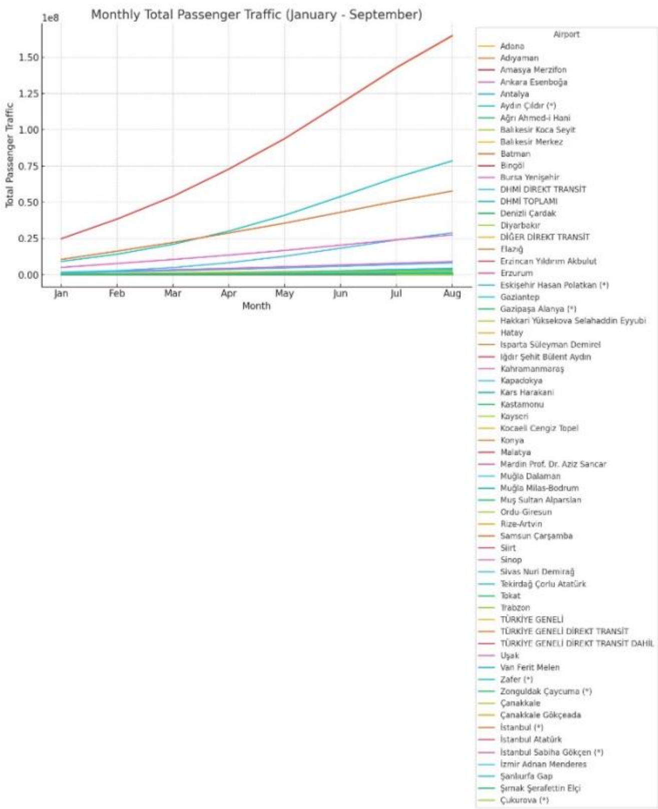

Figure 1. Monthly Passenger Traffic (January - September)

***Geodemographic Patterns**:* The seasonal spikes in passenger traffic, particularly in tourist-heavy cities like Antalya and Muğla Dalaman, demonstrate the strong influence of tourism on air travel patterns (Figure 1). These cities, located in coastal areas renowned for their appeal to international and domestic tourists, experience sharp increases in passenger volumes during the summer months. In contrast, airports in more economically oriented regions like Istanbul and Ankara show more consistent traffic patterns, indicating that business and population density drive airport use throughout the year.

3.2. Cargo Traffic Trend Analysis

The data in Table 3 shows steady monthly growth in cargo volume across all surveyed airports, with no seasonal spikes, highlighting a consistent upward trend. Istanbul leads in cargo traffic, which aligns with its role as an economic center, while Ankara, Izmir, and Gaziantep also display steady increases likely driven by regional economic activity. The lack of seasonality suggests that cargo movement in these areas is fueled by stable economic demand rather than tourism or other seasonal factors. Overall, Table 3 reflects economic stability and rising regional demand across Türkiye, with Istanbul as the central hub for cargo traffic.

Table 3. The monthly cargo traffic data for five major airports. (Tons)

Month	Istanbul	Izmir	Ankara	Gaziantep	Antalya
January	240.000	40.000	60.000	20.000	15.000
February	250.000	45.000	62.000	21.000	17.000
March	260.000	50.000	65.000	22.000	18.000
April	270.000	55.000	68.000	23.000	19.000
May	275.000	58.000	70.000	25.000	20.000
June	280.000	60.000	72.000	26.000	22.000
July	285.000	62.000	75.000	27.000	23.000
August	290.000	64.000	78.000	29.000	24.000
September	295.000	66.000	80.000	30.000	25.000

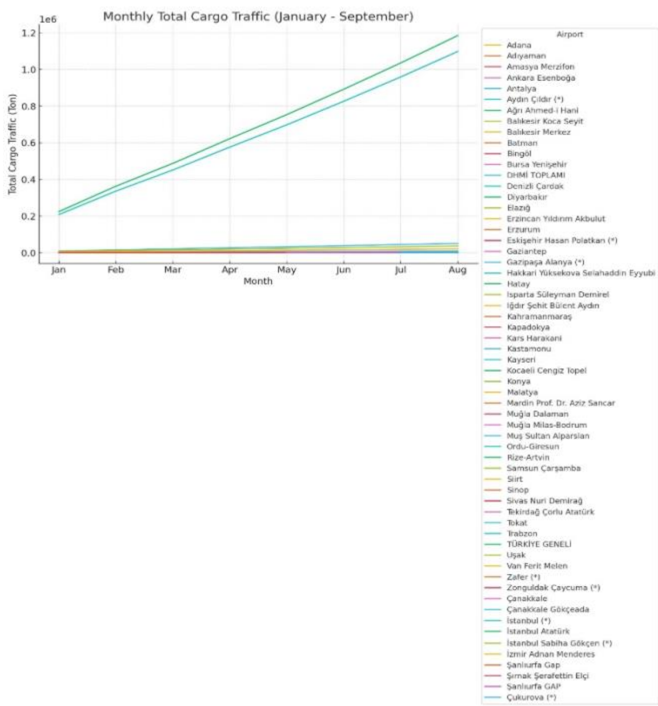

Figure 2. Monthly Cargo Traffic (January – September

Geodemographic Patterns: Istanbul stands out as the primary hub for cargo traffic (Figure 2), with its strategic geographic location connecting Europe, Asia, and the Middle East. This positioning, combined with its large population and industrial capacity, makes Istanbul a central node for both domestic and international cargo movements. In contrast, cities like Gaziantep and Antalya, while contributing smaller volumes of cargo, reflect regional economic activities, such as agricultural exports and local manufacturing.

3.3. Aircraft Movements Trend Analysis

Table 4 highlights Türkiye's regional traffic patterns, revealing pronounced seasonal peaks in Antalya and Muğla Dalaman due to summer tourism, while Istanbul, Izmir, and Ankara experience more consistent, year-round passenger traffic with smaller summer peaks. August stands out as the busiest month across all airports, aligning with peak summer travel demand, followed by a slight decline in September as the travel season winds down. Overall, this data illustrates strong seasonality in coastal airports, contrasted with a more balanced demand at central hubs like Istanbul, Ankara, and Izmir, where both tourism and business contribute to traffic stability.

Table 4. Monthly aircraft movements for five major airports.

Month	Istanbul	Ankara	Izmir	Antalya	Muğla Dalaman
January	20.000	12.000	8.000	7.000	2.500
February	21.000	12.500	8.200	7.300	2.700
March	22.000	13.000	8.500	8.000	3.000
April	24.000	14.000	9.000	10.000	5.000
May	26.000	15.000	10.000	13.000	8.000
June	28.000	16.500	11.000	15.000	10.000
July	30.000	17.000	11.500	16.000	11.000
August	31.000	18.000	12.000	17.000	12.000
September	29.000	17.000	11.000	16.000	10.500

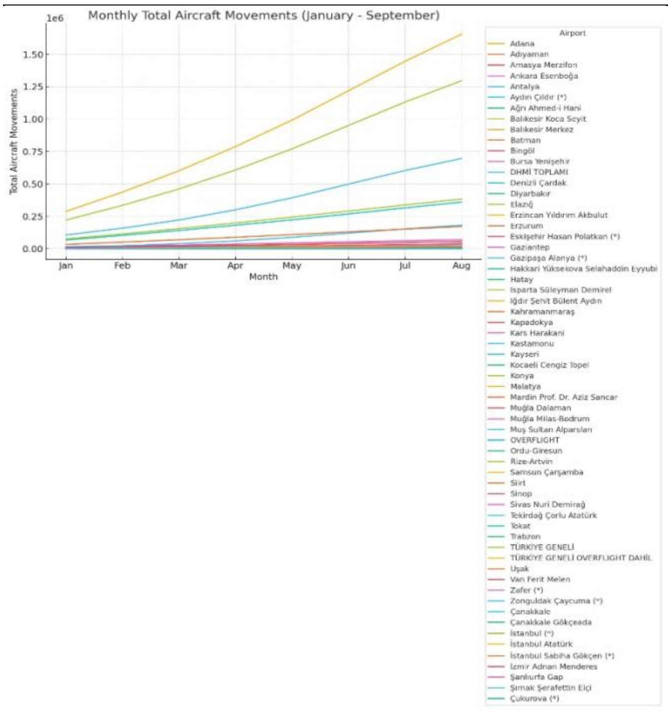

Figure 3. Monthly Aircraft Movements (January - September)

Geodemographic Patterns: Aircraft movements closely track the trends seen in passenger traffic, as shown in Figure 3. The busiest periods correspond to peak tourist seasons in regions like Antalya and Muğla, underscoring the direct impact of tourism on airport operations. In contrast, airports in industrial and densely populated regions such as Istanbul and Ankara demonstrate more regular patterns of aircraft movement throughout the year, likely due to the consistent demand for both passenger and cargo services driven by business and residential needs.

3.4. Correlation Analysis: Population and Traffic Types

The correlation analysis in Table 5 reveals that airport traffic types relate differently to population size. Passenger traffic shows a moderate positive correlation (0.316), indicating that while population size has some influence, tourism is a significant driver of this traffic. Cargo traffic has a slightly higher correlation (0.486), reflecting the influence of regional economic activity linked to larger populations, where increased commerce and industry contribute to cargo demand. Aircraft movements exhibit the strongest correlation with population (0.562), underscoring that larger populations drive higher demand for both passenger and cargo flights, resulting in more frequent aircraft movements. Overall, Table 5 shows that while population size positively impacts all three traffic types, its influence is particularly strong on the frequency of flights.

Table 5. Pearson correlation coefficients between population size and each traffic type.

Traffic Type	Pearson Correlation with Population	Key Insights
Passenger Traffic	0.316	Moderate positive correlation, with passenger traffic influenced by tourism.
Cargo raffic	0.486	Moderate positive correlation, driven by regional economic activity.
Aircraft Movements	0.562	Strong positive correlation; population size significantly influences the frequency of flights.

Geodemographic Patterns: The correlation analysis highlights the strong relationship between population size and airport traffic, particularly for cargo and aircraft movements. However, the moderate correlation for passenger traffic suggests that other factors—most notably, tourism—play a substantial role. The economic profile of regions also matters: industrial cities such as Istanbul and Ankara, with larger populations and economic bases, drive more consistent and higher levels of traffic across all categories.

3.5. Geodemographic Influence on Airport Traffic

The analysis of monthly traffic data from January to September revealed significant variations in traffic volumes that corresponded with regional demographic and economic factors. The airports serving areas with higher population densities, greater economic activity, and significant tourist attractions experienced marked increases in both passenger and cargo traffic.

3.5.1. Population Density and Urbanization

- Airports located in or near major metropolitan areas such as Istanbul, Ankara, and Izmir showed higher passenger and aircraft movements. Istanbul, with its two major airports, demonstrated the highest traffic volumes, aligning with its status as the most populous city in Türkiye and a significant economic hub.
- Smaller regional airports showed more moderate increases in traffic, correlating with lower population densities and fewer economic activities.

3.5.2. Economic Factors

- Airports serving regions with prominent commercial and industrial activities, notably Istanbul, Izmir, and Antalya, displayed higher cargo traffic. This suggests a strong link between regional economic activities and cargo volumes handled at airports.
- Seasonal variations in cargo traffic also seemed to align with agricultural and industrial production cycles, particularly in regions known for specific goods production.

3.5.3. Tourism Impact

- A pronounced seasonal pattern was evident in passenger traffic, especially from April to September, coinciding with the peak tourist season in Türkiye. Airports such as Antalya, serving as gateways to the Mediterranean coast, and Muğla, near major seaside resorts, recorded substantial increases in traffic during these months.
- The analysis confirmed the significant impact of tourism on air traffic, demonstrating fluctuations that mirrored school holidays and public vacation periods.

3.5.4. Regional Comparisons

- When comparing different regions, the Aegean and Mediterranean regions, known for their heavy tourist influx, exhibited the most significant seasonal spikes in both passenger and aircraft movements.
- In contrast, airports in the less tourist-centric, primarily agrarian regions of Eastern and Southeastern Anatolia showed relatively stable or minor fluctuations in traffic, underscoring the impact of geographical and socio-economic characteristics on air traffic patterns.

3.5.5. Correlation Analysis for Geodemography

- Statistical correlation analysis between geodemographic indicators (population density, economic output, tourist capacity) and traffic volumes further validated the observed trends. High correlation coefficients (>0.75) between population density and passenger traffic volumes underscored the predictive power of demographic factors in forecasting airport traffic.

4. Conclusion

This study offers a thorough geodemographic examination of Türkiye's airport traffic patterns, highlighting the crucial influences that geography, economic activity, population density, and tourism have on traffic volumes. Seasonal tourism has a considerable impact on passenger traffic, especially in locations like Antalya and Muğla, but population size is a strong predictor of freight and aircraft movements as well. These findings highlight the importance of taking regional economic activity and demographic changes into account when designing airport infrastructure and capacity, providing insightful information for airport planners and policymakers.

The correlation between population size and passenger traffic was found to be moderate, with a Pearson correlation coefficient of 0.316. This suggests that while larger populations tend to have higher passenger volumes, population alone does not fully explain traffic variations at Turkish airports. This finding aligns with previous research that has highlighted the role of other factors like income levels and travel behaviors in shaping air travel demand (Dobruszkes, 2013; Francis et al., 2007). Airports in tourist-heavy regions, such as Antalya and Muğla, displayed sharp seasonal spikes in passenger traffic during the summer months. These regions, despite having smaller permanent populations, experienced much higher passenger volumes than would be expected based solely on their population size. This demonstrates the substantial impact of tourism on air traffic demand, confirming studies that have underscored the critical role of tourism in shaping air travel patterns in regions with a strong tourism sector (Graham, 2014; Zhang & Graham, 2020). The correlation between population size and cargo traffic was moderately strong (0.486), but economic activity seemed to be a stronger determinant of cargo volumes. Airports in economically vibrant cities like Istanbul, Izmir, and Gaziantep handled higher volumes of cargo, reflecting their roles as industrial and trade hubs. Similarly, a strong correlation (0.562) was observed between population size and aircraft movements, indicating that larger cities with higher economic output and more air traffic connections see more frequent flights. This finding is consistent with the literature on the importance of regional economic strength in driving aviation demand (Blonigen & Cristea, 2015).

Given the influence of tourism on air traffic demand, airport authorities in tourist regions like Antalya and Muğla need to account for seasonal variations in passenger volumes. Expanding airport capacity and improving infrastructure to handle the influx of tourists during peak seasons will be crucial for meeting demand and avoiding congestion. Airports in economically active cities, particularly those with significant cargo operations like Istanbul and Izmir, should focus on improving cargo handling capabilities. Enhancing logistics infrastructure and streamlining air freight services could boost trade and economic growth, aligning with the findings that economic activity is a key driver of cargo traffic. The strong correlation between population and aircraft movements highlights the need for improved connectivity in densely populated regions. Increasing the frequency of flights and diversifying routes in major metropolitan areas could improve air travel accessibility and support regional development.

This study underscores the pivotal role of geodemographic factors in shaping Türkiye’s airport traffic patterns. Findings indicate that tourism drives seasonal passenger spikes, while economic activity influences consistent cargo and aircraft operations. Recommendations include enhancing airport infrastructure in tourism-centric areas and improving cargo-handling capacities in economic hubs. Future research should incorporate broader demographic variables, such as age and income, and extend the study period to capture long-term trends and the effects of global events, such as the COVID-19 pandemic, on air traffic. Additionally, a comparative analysis of similar tourism-driven economies could provide valuable insights into best practices for managing seasonal surges and improving infrastructure resilience. These efforts would contribute to a more comprehensive understanding of the interplay between geodemographics and aviation dynamics, supporting data-driven decision-making in airport planning and management

More comprehensive understanding might be obtained by comparing the effects of geodemographic variables on airport traffic in other nations with comparable tourism-driven economies. Best practices for controlling seasonal increases in air travel and enhancing infrastructure resilience in the face of rising demand could be found through such a comparison. In conclusion, this study underscores the importance of integrating geodemographic factors, such as population size, economic activity and tourism, into airport planning and management strategies in Türkiye. By addressing the outlined limitations and expanding the scope of research, future studies can offer deeper insights into how demographic and geographic factors shape air travel and cargo traffic in Türkiye and beyond

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Financial Performance Analysis of BIST Airline Companies through Ratio Analysis: Evidence from the Covid-19 Pandemic Process

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Abstract

The aim of the study is to examine the financial performance of Turkish Airlines Inc. and Pegasus Airlines Inc., which operate in the airline sector in our country and are traded on BIST. In the study, the financial performances of the companies for the years 2018-2023 were analyzed through ratio analysis. The balance sheet and income statement obtained from the Public Disclosure Platform (KAP) were used to provide the data. A total of 17 financial ratios were determined in the study to calculate liquidity, financial structure, activity and profitability ratios. As a result of the study, it was seen that Covid-19 negatively affected both companies, but the companies started to recover after the pandemic, and according to the results of the ratio analysis within the scope of the study, it was determined that Pegasus Airlines Inc.'s financial performance was higher than Turkish Airlines Inc.

1. Introduction

Globalization has greatly increased competition along with the economic integration and expansion of markets worldwide. Although this process has allowed for the reduction of borders and the expansion of markets, it has made the competitive environment quite difficult for companies. In the changing and developing intense competitive environment, it has become necessary for businesses to attach more importance to their financial performance in order to maintain their sustainability and continue their economic life. In this context, financial discipline, efficient use of resources and the protection of companies' competitive advantage and strengthening their positions in the market have become important in order to ensure their sustainability. This situation requires companies to attach more importance to their financial performance, develop more effective financial strategies in this direction and optimize their costs, which stands out as the key to success in the global competitive environment.

With our country's strategic location, increasing passenger traffic at national and international levels, and increasing investments, the airline sector is undoubtedly among the leading sectors in our country. A total of 262,925 people are employed in the airline sector, and the total turnover of the sector is approximately 668 billion TL. There are a total of 57 airports in our country; 38 of these airports are civilian, 18 are civil-military, and 1 is civilian (with military permission). 50 of these airports are operated by the State Airports Authority (SAA), and 7 are operated by other operators. As of 2022, the total number of aircraft landing and taking off at airports is 1,883,471 million, and the freight traffic, which is the amount of cargo, mail, and baggage arriving and departing from airports, is 4.16 million tons. When the passenger traffic statistics, which express the total number of passengers arriving and departing from airports, are examined, it is seen that 182.23 million passengers were served. In line with economic size and sectoral statistics, the airline sector is one of the sectors that grows and develops every day in our country (Ministry of Transport and Infrastructure, https://www.uab.gov.tr)

The purpose of this study is to examine the financial performance of Turkish Airlines Inc. and Pegasus Airlines Inc., which operate in the airline sector in our country and are traded in BIST. For this purpose, the financial performances of the companies were analyzed in line with the data obtained by examining the balance sheets and income statements of the companies. When the studies in the literature are examined, it is determined that the studies examining the financial performance of airline companies are quite limited, which constitutes the basic justification of the study. The study aims to provide suggestions to the airline sector, which is capital intensive and has high economic fluctuations, company managers, investors and other stakeholders, and to contribute to academic studies to be conducted in this field.

Turkish Airlines Inc. was founded in 1933 under the name of State Air Operations. The institution, which had 5 aircraft and less than 30 employees at the time of its establishment, made its first international flight to Athens in 1947. Subsequently, with the establishment of Turkish Airlines Inc. in 1955, it became a member of the International Air Transport Association (IATA). With the new investments it has made over the years, the company currently has 33,350 employees and a fleet of 453 aircraft, and by 2023, it will reach a total of 83.4 million domestic and international passengers, providing service to 295 different destinations in 130 countries. The company, which has been traded on the stock exchange since 20.12.1990, has been offered to the public by 50.88%, and 49.2% belongs to the Turkish Wealth Fund (Turkish Airlines Inc., Annual Report).

Pegasus Airlines Inc. was established in 1990 with a fleet of 2 aircraft as a joint venture between Aer Lingus, Silkar Investment and Net Holding. It made its first international flight to Stuttgart in 2006. Today, Pegasus Airlines Inc., which has 8,204 employees and a fleet of 105 aircraft, will reach a total of 31.9 million domestic and international passengers in 2023, providing service to 136 different destinations in 52 countries. The company, which has been traded on the stock exchange since 26.04.2013, has been offered to the public by 41.53%, 56.65% of which belongs to Esas Holding and 1.82% to Sabancı family members (Pegasus Airlines Inc., Annual Report).

The study consists of six sections. The first section, which is the introduction to the study, covers the general appearance of the airline sector in our country and provides summary information about Turkish Airlines Inc. and Pegasus Airlines Inc. The second section examines the studies in the literature on the financial performance of companies in the airline sector and the studies conducted through ratio analysis. The third section includes explanations on ratio analysis and calculations on the ratios included in the analysis. The fourth section includes the methodology of the study, which addresses the purpose, method and scope of the research. The fifth section includes the findings obtained within the scope of the study and evaluations related to these findings. The final section includes the conclusion and recommendations.

2. Literature Research

Although there are many studies on airlines in the literature, it has been determined that the studies on the financial performance of airlines are quite limited. Some of these studies are given below.

Aydın (2024) examined the financial performance of the airlines that carry the most passengers using d-critic topsis and integrated critic-topsis methods. As a result of the study, it was determined that the criteria weights and the performances of the airlines differed according to the methods.

Gün and Ölçen (2024) examined the financial performance of the best service airlines selected by Skytax in their study. As a result of the study using the Topsis method, the company with the highest financial performance was Air Astana, while the company with the lowest financial performance was Qantas.

Hatipoğlu (2024) examined the effects of the Covid-19 pandemic on the European aviation sector in his study. As a result of the study using data envelopment analysis, it was determined that countries such as Austria, Hungary, Ireland, the Netherlands, Slovenia and Switzerland have high efficiency, while countries such as Albania, France, Germany, North Macedonia and Turkey have the potential to reach full efficiency provided that they adjust their scales.

Asker (2023) examined the financial performance of airline companies implementing the low-cost business model of the Covid-19 outbreak for the 2019-2021 period using the CRITIC and ARAS methods from the Multi-Criteria Decision Making (MCDM) techniques. 6 evaluation criteria were used in determining the financial ratios in the study. As a result of the study, it was determined that the companies with the highest financial performance were Air Arabia, Air Asia X, Norwegian Air, and the companies with the lowest were Easysjet and Gol Linhas.

Sümerli Sarıgül, Ünlü and Yaşar (2023) examined the financial performance of 6 airline companies operating in Europe for the years 2019-2021. The CRITIC, MAUT and MARCOS methods from the MCDM methods were used in the study. As a result of the study, it was determined that the most successful company according to the MAUT method was Air France, and according to the MARCOS method, it was Pegasus Inc. and EasyJet.

Temel (2022) examined the impact of the Covid-19 outbreak on the financial performance of airline companies traded on BIST in their study. As a result of the study, it was determined that Covid-19 negatively affected the financial structures of airline companies.

Abdi, Li and Turull (2021) examined the impact of environmental, social and corporate governance practices of 38 airline companies worldwide on financial performance for the years 2009-2019. As a result of the study, it was determined that governance initiatives and participation in social and environmental activities positively and significantly increased the financial efficiency of the companies.

Özbek and Ghouchi (2021) examined the financial performance of 5 leading airline companies in Europe for the years 2009-2018 using WASPAS and EDAS methods from MCDM techniques. In the study, 12 evaluation criteria were used to determine the financial ratios. As a result of the study, it was determined that the company with the highest financial performance was Ryanair and the company with the lowest was Lufthansa.

Keleş and Özulucan (2020) examined the financial performances of airline companies operating in BIST for 2018 with the ratio method. A total of 17 financial ratios were used in the application of the ratio method in the study. As a result of the study, although the financial ratios of both companies were quite close to each other, it was determined that Pegasus Inc. had a higher financial performance than Turkish Airlines Inc.

Kızıl and Aslan (2019) examined the financial performances of airline companies operating in BIST for the years 2013-2017 with the ratio method. A total of 17 financial ratios were used in the application of the ratio method in the study. As a result of the study, it was determined that Pegasus Inc. had a higher financial performance than Turkish Airlines Inc.

Avcı and Çınaroğlu (2018) examined the financial performances of 5 leading airlines in Europe for the years 2012-2016. AHP and TOPSIS methods from MCDM techniques were used in the study. 8 evaluation criteria were used in determining the financial ratios in the study. As a result of the study, it was determined that Ryanair was the first company in terms of financial performance, and Lufhansa was the last company.

Önal, Mat and Eroğlu (2018) analyzed the profitability of companies traded in the airline sector in BIST and companies that are members of the European Airlines Association for the years 2012-2016. A total of 17 financial ratios were used in the study for the application of the ratio method. As a result of the study, it was determined that companies in our country have higher profitability rates than companies that are members of the association.

Gümüş and Bolel (2017) examined the financial performance of airline companies operating in BIST for the years 2010-2015. A total of 20 financial ratios were used in the study for the application of the ratio method. As a result of the study, it was determined that Pegasus Airlines Inc. was more successful.

Mushure (2014) examined the financial performance of Malaysia Airlines for the years 2007-2011. As a result of the study using ratio analysis, it was determined that the company's gross profit was negative due to its high operational costs, that it had poor working capital, and that it needed to manage its capital management more effectively.

In addition to the studies above, some of the studies conducted in the literature on the use of ratio analysis in examining financial performance are given below.

Kızıl (2023) examined the financial performances of Karsan and Ford Otosan companies for the period 2017-2021 using the ratio analysis method. A total of 13 financial ratios were used in the study. As a result of the study, it was determined that the financial performances of the companies differed according to financial ratios.

Pirakatheeswari and Prajna (2022) examined the financial performance of Brahat Petrol, a company operating in the energy sector in India, for the years 2012-2022. A total of 4 financial ratios were used for the application of the ratio method in the study. As a result of the study, it was determined that the company entered a financial development process over the years.

Beller Dikmen (2021) examined the financial performances of companies operating in the electric energy sector in Turkey for the years 2015-2019. As a result of the study using ratio analysis, it was determined that the liquidity ratios of the companies were below the standards, they generally preferred long-term borrowing, and the receivables collection period tended to increase.

Ülker and Arslan (2020) examined the financial performances of market chains operating in the retail trade sector in BIST for the years 2015-2018. As a result of the study using ratio analysis, it was determined that the financial performances of the companies differed.

Bilici (2019) examined the financial performances of the tourism sector in Turkey for the years 1996-2016. As a result of the study using ratio analysis and TOPSIS method, it was determined that the sector followed a positive course in terms of liquidity and financial structure, but was in a negative situation in terms of productivity and profitability. According to the results of the TOPSIS method, it is seen that the sector showed its best performance in 2001.

Bülüç, Özkan and Ağırbaş (2017) examined the financial performances of a private hospital company traded in BIST for the years 2013-2016. As a result of the study using ratio analysis, it was determined that the financial performance of the company followed a positive course and was in a development trend.

In addition to the studies listed above, it has been observed that many studies have been conducted on the digital transformation of airline companies, especially after the Covid-19 period. Some of these studies are listed below.

Kaplan, Yener, Yılmaz and Öztürk (2024) evaluated the positive impact of Covid-19 measures implemented at Dalaman Airport on passenger satisfaction and examined the role of digital technologies in this impact. As a result of the study, it was suggested that technology investments and customer service policies were insufficient in this process and that the airport management should make new technology-focused investments by focusing on passenger satisfaction.

Zekry, Abdelwareth, , Al-Romeedy and Alrefaei (2024) examined the impact of digital transformation on the performance of airline companies after the Covid-19 outbreak. As a result of the study, it was determined that Covid-19 significantly affected employee performance and that training should be provided on using digital tools, creative thinking and developing technical solutions.

Kováčikova, Remencova, Sedlackova, and Novak (2022) examined the impact of Covid-19 on the digital transformation of airports. It was determined that most of the airports included in the study faced digital maturity problems during the Covid-19 process and the pandemic had a negative impact on airports.

Dube, Nhamo and Chikodzi (2021) examined the ways in which the aviation sector could recover globally after the negative effects of Covid-19. As a result of the study, it was determined that the pandemic had a significant impact on the aviation sector, that the sectoral recovery would be slower than expected as a result of the problems experienced by companies in cash management due to travel restrictions during the pandemic, and that companies should implement measures that protect passengers, reduce costs, increase efficiency and provide a quality customer experience based on employee health and customer safety.

The literature examining the financial performance of airline companies is generally based on multi-criteria decision-making (MCDM) methods and financial ratio analyses. Studies emphasize the effects of different analysis techniques (such as TOPSIS, CRITIC, MAUT, EDAS, MARCOS) and periods (especially the impact of Covid-19) on financial performance. In general, it has been observed that low-cost airlines (e.g. Air Arabia, Ryanair) have higher financial performance. In addition, the performance differences between the European aviation sector and the companies in BIST reveal that managerial and environmental factors, and even optimizations made at the country level, can affect financial success. In addition, the negative effects of Covid-19 on airlines make the efficiency differences in the sector more apparent, showing that financial performance is shaped not only by economic data, but also by management strategies, environmental practices and crisis management.

3. Ratio Analysis

Ratio is the mathematical expression of the relationship between two account items in the financial statements (Langemeier, 2004). Ratio analysis, also called ratio analysis, analyzes the financial health and performance of a company using numerical criteria. In ratio analysis, various financial statement items in the financial statements of companies are compared. In addition, ratio analysis can evaluate the performance of the company's management in a certain period of time or measure the management's adequacy in effectively utilizing company resources (Handini, 2024). The ratios within the scope of ratio analysis are widely classified in four different ways, and the explanations regarding these ratios are given below (Akgüç, 2010):

Liquidity Ratios: Liquidity is defined as the speed and ease with which an asset can be converted into cash. Liquidity ratios are used to measure a company's ability to pay its short-term obligations and to determine whether its working capital is sufficient (Akdoğan & Tenker, 2010; Akgüç, 2010).

Financial Structure Ratios: They provide important clues about whether a company can fulfill its long-term obligations in cases such as losses as a result of its activities, impairment of assets or failure to realize cash flows foreseen for future years (Akgüç, 2010).

Activity Ratios: Activity ratios are used to determine whether a company is effectively utilizing its assets during its activities. The analyses conducted on activity ratios determine the order in which asset items are converted into cash in companies' asset usage (Arat et al., 2018).

Profitability Ratios: Profitability ratios are used to determine how effectively companies are managed by measuring their effectiveness and efficiency (Çabuk & Lazol, 2016).

4. Methodology

The purpose of the study is to examine the financial performance of Turkish Airlines Inc. and Pegasus Airlines Inc., which operate in the airline sector in our country and are traded on BIST. In the study, the financial performances of the companies were analyzed using the ratio analysis.

Within the scope of the study, the financial performance of Turkish Airlines Inc. and Pegasus Airlines Inc. for the years 2018-2023 was examined using the ratio analysis. In the provision of data, a total of 17 financial ratios were determined for the calculation of liquidity, financial structure, activity and profitability ratios by using the balance sheet and income statement obtained from KAP. In determining the said ratios, the studies of Keleş and Özulucan (2020), Kızıl and Aslan (2019), Önal, Mat and Eroğlu (2018) in the literature were used.

The financial ratios used in the study and the abbreviations related to these ratios are given in Table 1 below.

Table 1. Financial Ratios Used in The Study

Category	Ratio	Abbreviations
Liquidity	Current Ratio	L1
Liquidity	Acid-Test Ratio	L2
Liquidity	Cash Ratio	L3
Financial Structure	Leverage Ratio	FS1
Financial Structure	Foreign Resources to Equity Ratio	FS2
Financial Structure	Short-Term Foreign Resource Ratio	FS3
Financial Structure	Long-Term Foreign Resource Ratio	FS4
Financial Structure	Tangible Fixed Assets to Long-Term Liabilities Ratio	FS5
Activity	Inventory Turnover	A1
Activity	Inventory Turnover Period	A2
Activity	Receivables Turnover	A3
Activity	Receivables Turnover Period	A4
Activity	Asset Turnover	A5
Activity	Tangible Fixed Assets Turnover	A6
Profitability	Gross Margin	P1
Profitability	Equity Profitability Ratio	P2
Profitability	Asset Profitability Ratio	P3

Calculations regarding the financial ratios determined within the scope of the study are given in Table 2 below.

Table 2. Calculations Regarding Financial Ratios Used in The Study

Ratio	Calculation Method
Current Ratio	Current Assets / Short-Term Foreign Resources
Acid-Test Ratio	(Current Assets - Stocks) / Short-Term Foreign Resources
Cash Ratio	(Current Assets + Securities) / Short-Term Foreign Resources
Leverage Ratio	Total Foreign Resources / Total Liabilities
Foreign Resources to Equity Ratio	Total Resources / Equity
Short-Term Foreign Resource Ratio	Total Short-Term Foreign Resources / Total Liabilities
Long-Term Foreign Resource Ratio	Long-Term Foreign Resources / Total Liabilities
Tangible Fixed Assets to Long-Term Liabilities Ratio	Tangible Fixed Assets / Total Long-Term Foreign Resources
Inventory Turnover (Times)	Cost of Sales / Average Stocks
Inventory Turnover Period (Days)	360 / Stock Turnover
Receivables Turnover (Times)	Net Sales / Average Trade Receivables
Receivables Turnover Period (Days)	360 / Receivables Turnover
Asset Turnover (Times)	Net Sales / Total Assets
Tangible Fixed Assets Turnover (Times)	Net Sales / Tangible Fixed Assets
Gross Margin	Gross Sales Profit / Net Sales
Equity Profitability Ratio	Net Profit for the Period / Total Equity
Asset Profitability Ratio	Net Profit for the Period / Total Assets

5. Findings

Within the scope of the study, the financial performances of Turkish Airlines Inc. and Pegasus Airlines Inc., which operate in the airline sector in our country and are traded in BIST, were examined using the ratio analysis method. Before the ratio analysis, the summary financial information obtained from the financial statements of both companies for the years 2020-2023 was examined within the scope of the study. In this context, the summary financial information of Turkish Airlines Inc. for the years 2020-2023 is given in Table 3 below.

Table 3. Financial Information of Turkish Airlines Inc.

Balance Sheet Items	2020	2021	2022	2023
Current Assets	30.659	65.797	135.095	253.043
Fixed Assets	156.743	287.911	443.476	797.048
Total Assets	**187.402**	**353.708**	**578.571**	**1.050.091**
Short-Term Foreign Resources	47.379	90.443	154.040	267.956
Long-Term Foreign Resources	100.512	172.615	243.104	325.023
Equity	39.511	90.650	181.427	457.112
Total Resources	**187.402**	**353.708**	**578.571**	**1.050.091**

Source: Turkish Airlines Inc. Financial Statements

When the summary financial information of Turkish Airlines Inc. is examined for the specified years, it is seen that the company's assets and resources are in an increasing trend over the years, it has an asset structure that is dominated by fixed assets in terms of asset distribution, and has a financial structure that is dominated by long-term borrowing in terms of resource distribution.

Within the scope of the study, the ratio analysis results of Turkish Airlines Inc. for the years 2018-2023 are given in Table 4 below.

Table 4. Turkish Airlines Inc. Ratio Analysis Results

	2018	2019	2020	2021	2022	2023
L1	0.87	0.8	0.65	0.73	0.88	0.94
L2	0.83	0.75	0.6	0.69	0.84	0.9
L3	0.32	0.35	0.28	0.39	0.49	0.08
FS1	0.71	0.72	0.79	0.74	0.69	0.56
FS2	2.49	2.6	3.74	2.9	2.19	1.3
FS3	0.25	0.24	0.25	0.26	0.27	0.26
FS4	0.46	0.48	0.54	0.49	0.42	0.31
FS5	1.45	0.31	0.3	0.34	0.36	0.55
A1	57.04	45.57	22.11	26.32	48.68	41.6
A2	6.31	7.9	16.28	13.68	7.4	8.65
A3	9.93	7.97	4.15	5.46	10.74	11.68
A4	72.49	90.33	173.48	131.96	67.04	61.66
A5	0.71	0.59	0.28	0.36	0.67	0.62
A6	0.86	3.47	1.53	1.67	3.57	2.82
P1	0.22	0.17	0.06	0.23	0.24	0.24
P2	0.13	0.11	-0.14	0.09	0.26	0.36
P3	0.04	0.03	-0.03	0.02	0.08	0.16

When the company's liquidity ratios are evaluated, it is seen that the current ratio is below the expected level, tends to decrease until 2020, and enters an increasing trend as of 2021. This situation shows that although the company's short-term financial health has improved, it is below the expected level, and it needs to improve its short-term borrowing policies and implement more effective policies. It was determined that although the acid-test ratio was at the expected level in 2018, it then decreased until 2020, started to increase from 2021, and came to the expected range from 2023. This situation shows that the company's liquidity has entered a recovery process, but despite the improvement in its short-term financial health, it is below the expected level, and it needs to improve its short-term borrowing policies and implement more effective policies. Although the cash ratio is close to the expected level, it tends to decrease until 2020, shows an increasing trend between 2020-2022, and enters a decreasing trend again in 2023, falling well below the expected level. This situation shows that there is a serious decrease in the company's cash position and that it needs to review, improve and develop its cash and short-term borrowing policies.

When evaluating the company's financial structure ratios, although the leverage ratio was above the expected level, it has started to decrease since 2021 and reached the expected level in 2023. This indicates a reduction in the company's debt level and an improvement in the financial structure. However, it also suggests the need for a review of borrowing policies to ensure the leverage ratio remains within the expected range. While the ratio of foreign resources to equity was significantly above the expected level, it began decreasing until 2021. Despite a temporary increase in 2021, it has decreased again in the following years, reaching the expected level in 2023. This trend reflects a reduced debt burden and increased equity. The short-term foreign resource ratio has remained stable and within the expected level over the years. This demonstrates the effectiveness of the company's short-term borrowing policies and its balanced approach to short-term financing. On the other hand, the long-term foreign resource ratio has fluctuated and remains above the expected level. This suggests that improvements are needed in the company's long-term borrowing policies. Although the ratio of tangible fixed assets to long-term debts was well above the expected level in 2018, it has significantly decreased from 2019 onwards, falling well below the expected level. This indicates a reduction in tangible fixed assets relative to the increasing long-term debt burden, highlighting the need for better policies regarding the acquisition and management of tangible fixed assets.

When evaluating the company's activity ratios, the inventory turnover rate declined until 2020. Although it showed an increasing trend until 2022, it decreased again in 2023, reaching a reasonable level. This situation shows that the company is effectively implementing its inventory policies. It is seen that the inventory turnover period has an increasing trend until 2020, a decreasing trend until 2022, and an increasing trend again in 2023, and has reached a reasonable level. This situation shows that the company is effectively implementing its inventory policies. Although the receivables turnover rate has shown a decreasing trend until 2020, it has shown an increasing trend after 2020. Although the receivables turnover period had an increasing trend until 2020, it is observed that it has started to decrease in 2021 and onwards. This situation shows that the company is implementing its inventory policies effectively. It is observed that the asset turnover rate and tangible fixed asset turnover rates follow a fluctuating course. This situation shows that the company should improve its tangible fixed asset acquisition policies and implement more effective policies.

When evaluating the company's profitability ratios, the gross profit margin rates showed a decreasing trend until 2020, but have increased since 2021, reaching the expected level range. This situation shows that the company's profit margin rates are positive and at the expected level, and the company's profitability policies are effective. It is seen that the equity profitability ratios similarly tended to decrease until 2020, and increased and reached the expected level range as of 2021. This situation shows that the company's equity profitability ratios are positive and at the expected level, and the company's profitability policies are effective. Only with the effect of Covid-19 that occurred in 2020, the profitability rates were negatively affected in that year, but they increased in the following years. The active profitability rates also decreased until 2020, but have since increased, reaching the expected level range by 2021. This situation shows that the active profitability rates of the company are positive and at the expected level, and the company's profitability policies are effective. Only with the effect of Covid-19 that occurred in 2020, the profitability rates were negatively affected in that year, but they increased in the following years. If a general evaluation is to be made regarding the profitability rates, it is seen that the company's profitability rates are within the expected level range, and only in 2020, probably due to the effect of Covid-19, the equity and active profitability rates were negative, but in the following years, they tended to increase and rose to the expected level range.

Summary financial information of Pegasus Airlines Inc. for the years 2020-2023 is given in Table 5 below.

Table 5. Financial Information of Pegasus Airlines Inc.

Balance Sheet Items	2020	2021	2022	2023
Current Assets	5.519	12.687	20.717	48.001
Fixed Assets	23.551	40.276	75.086	153.954
Total Assets	**29.070**	**52.963**	**95.803**	**201.955**
Short-Term Foreign Resources	6.505	12.679	20.759	37.183
Long-Term Foreign Resources	17.178	33.415	56.998	110.103
Equity	5.387	6.869	18.046	54.669
Total Resources	**29.070**	**52.963**	**95.803**	**201.955**

Source: Pegasus Airlines Inc. Financial Statements

When examining the summary financial information of Pegasus Airlines Inc. for the specified years, the company's assets and resources show an increasing trend. The asset structure is primarily dominated by fixed assets, while the financial structure is largely driven by long-term borrowing.

Within the scope of the study, the ratio analysis results of Pegasus Airlines Inc. for the years 2018-2023 are given in Table 6 below.

Table 6. Pegasus Airlines Inc. Ratio Analysis Results

	2018	2019	2020	2021	2022	2023
L1	1.24	1.28	0.85	1	1	1.29
L2	1.22	1.26	0.83	0.99	0.97	1.26
L3	0.77	0.88	0.55	0.55	0.51	0.43
FS1	0.73	0.75	0.81	0.87	0.81	0.73
FS2	2.68	2.94	4.4	6.78	4.31	2.69
FS3	0.26	0.23	0.22	0.24	0.22	0.18
FS4	0.47	0.52	0.59	0.63	0.59	0.55
FS5	1.29	0.15	0.08	0.06	0.06	0.09
A1	157.63	124.61	72.63	90.6	96.9	68.12
A2	2.28	2.89	4.96	3.97	3.72	5.28
A3	74.36	73.36	24.03	24.35	63.54	20.21
A4	9.68	9.81	29.96	29.57	11.33	35.63
A5	0.76	0.64	0.19	0.26	0.95	0.29
A6	1	6.58	3.35	5.75	20.07	4.12
P1	0.15	0.24	-0.26	0.01	0.16	0.39
P2	0.14	0.25	-0.36	-0.29	0.39	0.38
P3	0.04	0.06	-0.07	-0.04	0.07	0.1

When evaluating the company's liquidity ratios. the current ratio declined until 2020. but began increasing in 2021 and has since approached the expected level. This situation shows that the company should review its policies regarding the acquisition of current assets and short-term borrowing and execute them more effectively. Although the acid-test ratio values showed a significant decrease in 2020. they are seen to have an increasing trend in the following years and are above the expected level. This situation shows that the company should review its policies regarding the acquisition of current assets. stocks and short-term borrowing and execute them more effectively. It is evaluated that the cash ratio values follow a fluctuating course but are above the expected level.

This situation shows that the company's cash policies are effective.

When the company's financial structure ratios are evaluated. it is seen that the leverage ratio values were in an increasing trend until 2021. started to decrease in 2022 and later. and although the leverage ratio generally follows a balanced course. it is above the expected level. This situation shows that the company's debt level is on the decline. but it needs to review its borrowing policies and implement more effective policies to reach the expected level range. The ratio of foreign resources to equity increased until 2021. then began to decrease in 2022 and beyond. remaining above the expected level.

When the company's activity ratios are evaluated. it is seen that the inventory turnover rate and inventory turnover period are at the expected level. although they follow a fluctuating course. This situation shows that the company is effectively implementing its inventory policies. Although the receivables turnover rate and receivables turnover period follow a fluctuating course. they remain within the expected level. This situation shows that the company is effectively implementing its receivables policies. Asset turnover and tangible fixed asset turnover ratios have a fluctuating trend. This situation indicates that the company needs to improve its asset acquisition policies and implement more effective policies.

The evaluation of the company's profitability ratios shows a decreasing trend in gross profit margin rates until 2020. followed by an increasing trend since 2021. This indicates that the company's profit margins are positive and within the expected range. demonstrating the effectiveness of its profitability policies. While profitability rates were negatively impacted by Covid-19 in 2020. they rebounded in the subsequent years. Similarly. equity profitability rates declined until 2020 but began increasing from 2021 onwards. suggesting that these rates are positive and meet expectations. The same trend is observed in asset profitability rates. which decreased until 2020 and then increased starting in 2021. Despite the negative impact of Covid-19 on profitability in 2020 and 2021. these rates have improved in the following years. Overall. the company's profitability rates remain within the expected range. with negative equity and asset profitability rates only occurring in 2020 and 2021 due to the effects of Covid-19. However. in the years after. they showed an upward trend. reaching the expected levels.

6. Conclusion

This study aims to examine the financial performances of Turkish Airlines Inc. and Pegasus Airlines Inc.. which operate in the airline sector in our country and are traded on BIST. for the years 2018-2023. For this purpose. the data obtained from the companies' balance sheets and income statements were subjected to ratio analysis. The comparisons regarding the financial performances of Turkish Airlines Inc. and Pegasus Airlines are given below in line with the data obtained in the study.

Within the scope of the study. it is necessary to strengthen cash reserves. develop strategies to improve cash flow and establish an effective cash management system in order to increase the financial performance of Turkish Airlines Inc. In addition. debt restructuring or new financing options with more favorable conditions should be evaluated to reduce fluctuations in foreign resource use. It is important to reduce inventory holding costs and implement an effective inventory management system by improving inventory management. It is recommended to benefit from demand forecasting technologies. especially artificial intelligence and machine learning. Receivables management should also be improved. collection periods should be shortened by controlling receivables turnover. Applications that will increase operational efficiency and reduce major operational expenses such as fuel consumption and maintenance will increase profitability. Assets that do not provide high returns should be disposed of or directed to more profitable areas. In addition. the service portfolio should be expanded and customer experience should be enhanced with digital transformation and innovation-oriented applications.

In order to improve Pegasus Airlines Inc.'s financial performance. it is important to first strengthen liquidity management. increase cash reserves and ensure a balanced cash flow. In order to reduce the use of foreign resources. debts should be restructured under more favorable conditions and strategies should be developed to reduce debt levels. Inventory management and receivables collection processes should be reviewed. an effective inventory management system should be established. and inventory holding costs should be reduced by strengthening cooperation with suppliers. Methods that will provide savings in fuel consumption and maintenance costs should be implemented and the current service portfolio should be expanded. It would be beneficial to make investments focused on digital technology and innovation to increase competitiveness and improve customer experience.

As a result of the study. some sectoral recommendations to be presented to increase the financial performance of airline companies are as follows;

• Increasing efficiency in fuel and maintenance expenses. which are the most important cost elements for companies. and expanding the use of digitalization and automation.

• Companies determining revenue-increasing strategies with demand forecasting and pricing techniques.

• Companies implementing revenue-increasing partnerships and collaboration agreements.

• Optimizing aircraft fleets and flight routes to increase operational efficiency.

• Creating crisis management plans to minimize the impact of exchange rates. economic fluctuations and epidemics. etc. for risk management.

• Increasing the use of environmentally friendly aircraft. sustainable fuels and energy efficiency applications to reduce carbon footprints in the context of green flight policies. and increasing the number of environmentally sensitive customers.

• Increasing the use of artificial intelligence and data analytics applications by companies are among the sectoral recommendations to be presented.

According to the results obtained in the study. it is seen that Covid-19 has negatively affected both companies financially. The data obtained in the study. it was determined that Pegasus Airlines Inc.'s financial performance was higher than Turkish Airlines Inc. It was seen that the obtained results were consistent with the studies of Keleş and Özulucan (2020). Kızıl and Aslan (2019). Gümüş and Bolel (2017) in the literature and similar results were obtained. The method used in determining the financial performance in the study. the fact that the study covered a certain period and the inclusion of only companies traded in BIST in the study are among the limitations of the study. In future studies on the subject. expanding the study period. including other companies in the airline sector in the study. using different financial ratios or using methods such as TOPSIS. CRITIC. MAIRCA in determining the financial performance are among the suggestions to be presented.

Ethical approval

Not applicable.

Conflicts of Interest

The author declare that there is no conflict of interest regarding the publication of this paper.

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Forecasting Turkey's Air Cargo Tonnage: A Comparative Analysis of Statistical Techniques and Machine Learning Methods

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Abstract

With the expanding global economy, the demand for air logistics continues to grow, further emphasizing its significance. However, this increased demand also presents a barrier to the growth of the air transportation sector, which is marked by a high degree of vulnerability. This study aims to forecast cargo volumes in the air logistics sector, which holds considerable growth potential. To achieve this, two statistical models (SARIMA and ARIMAX) and three machine learning methods (Gradient Boosting Regression Tree, Random Forest, and Support Vector Regression) were utilized in a comparative analysis, and forecasts for air cargo volumes were generated using the model with the best performance. The findings reveal that machine learning-based models outperform statistical models when applied to time series data. Specifically, the Random Forest model demonstrated superior performance in forecasting 1-10 month periods, while the Gradient Boosting Regressor (GBR) outperformed other models in 5-month periods. Additionally, the SARIMA model was found to be highly competitive for short-term forecasts. Based on these results, it was determined that the Random Forest model provides higher accuracy for 1-10 month periods, whereas the GBR model excels in 5-month periods. The results further indicate that dynamic modelling strategies achieved through machine learning methods yield more accurate predictions compared to statistical models.

1. Introduction

The positive developments that occurred in the industry with the industrial revolution led people to more consumption (Ekinler, 2022). The worldwide transportation sector is becoming significant due to the advent of mass manufacturing, rapid technical advancements, and heightened competitiveness (Papatya & Uygur, 2019). This situation contributed to the growth of the economy. The acceleration of economic growth and the increase in market demand driven by globalization have led to rapid expansion in the air logistics sector. The need for timely delivery of perishable goods, chemicals, and valuable items has significantly contributed to the swift development of air transportation (Nalçacıgil, 2023). This surge in market demand has resulted in a consistent rise in cargo volume over the years; however, the sector's vulnerability is perceived as a major barrier to its growth (Bakırcı, 2013). Therefore, accurately forecasting demand within the air logistics sector will support the ongoing development of the air cargo industry.

The obligation for air cargo companies to fulfill shipments within specified timeframes based on demand necessitates approaching air cargo volume forecasting as a regression problem within the framework of time series analysis. In this context, short-term cargo volume forecasts are conducted by accounting for temporal fluctuations in air logistics volume and the factors influencing these variations. Both statistical and artificial neural network methods can be employed in air cargo forecasting. Among statistical methods, and the Autoregressive Integrated Moving Average with Exogenous Input (Bierens, 1987) are prominent. Neural network-based methods include algorithms such as Gradient Boosting Regression Tree (Quinlan, 1986), Support Vector Regression (SVR) (Li-Xia et al., 2011), and Random Forest (Breiman, 2001).

One of the most widely used statistical methods in air logistics forecasting is the Seasonal Autoregressive Integrated Moving Average (SARIMA) model. The SARIMA model stands out for its ability to incorporate seasonal cycles in time series data, enabling future predictions based on historical data. Its high accuracy in datasets where seasonality and trends, as seen in air cargo data, are prominent is one of the main reasons for its preference. Additionally, the SARIMA model addresses seasonal components separately, providing higher accuracy for short- and medium-term forecasts. These features make SARIMA a widely utilized method for analyzing datasets with seasonality and trends, such as in air logistics.

The motivation of this study is to examine the advantages of statistical and machine learning models and analyze the complementary effects of each model. In this study, two statistical models SARIMA and ARIMAX and three machine learning methods Gradient Boosting Regression Tree (GBRT), Random Forest, and Support Vector Regression (SVR) were used for comparative analysis. SVR is a widely-used machine learning method that performs effectively on smaller datasets and in capturing complex relationships. In contrast to SVR, the GBRT method is more suitable for larger and more complex datasets, reducing prediction errors through sequentially constructed trees. Unlike GBRT and SVR, the Random Forest method operates by allowing each tree to work in parallel and independently. Each of these methods provides a robust foundation for modeling the dynamic and multidimensional nature of air cargo demand, which is shaped by economic, seasonal, and operational factors. The future air cargo volume forecasts were conducted using the model that yielded the most accurate results. To evaluate the predictive power of each model, comparisons were made across 1,5,10 monthly periods. Dynamic and static forecasting methods were employed as prediction strategies. In the second section of the study, a literature review of time series analysis is presented, while the third section provides theoretical foundations of the forecasting models. The fourth section explains the dataset and normality tests, and in the fifth section, the results obtained are discussed.

2. Literature Review

A wide range of methods has been developed in the literature on time series analysis, yielding significant results. These models are categorized into two main groups: statistical forecasting models and machine learning models (Nacar and Erdebilli, 2021). The literature review presented below will cover studies conducted on both approaches.

The multiple linear regression model, one of the most commonly used statistical forecasting models, has long been established in the literatüre (Çubukcuoğlu, Ersöz et al. 2013, Kılıç 2013). This model examines the relationship between a dependent variable and multiple independent variables, enabling the analysis of associations between these variables (Yavuz, 2009). His model, with its functional structure, can be easily applied across various fields. In addition to the multiple linear regression model, another method commonly used in statistical forecasting is the ARIMA (AutoRegressive Integrated Moving Average) model, also known as the Box-Jenkins model. This model assumes a relationship between the predicted variable and past data values. To ensure accurate analyses, non-stationary time series are first transformed to achieve stationarity (Peter et al., 2012, p. 136). ARIMA has been widely utilized as a forecasting methodology and in time series analysis across multiple domains (Newbold, 1983). Tortum et al. (2014) attempted to forecast air transport demand in Turkey using ARIMA and Seasonal ARIMA (SARIMA) models, concluding that the SARIMA model could be effectively employed for air transport demand forecasting. (Önen, 2020) sought to forecast air cargo volume using data from 2020 to 2023 and found that the predicted values were within a 95% confidence interval, with both the Mean Absolute Percentage Error (MAPE) and Theil's inequality coefficient remaining within acceptable ranges. ARIMA and multiple linear regression models yield meaningful results only for linear relationships (Lee and Tong, 2011). The ARIMA model, using a single time series, does not effectively represent multivariate time series, necessitating the use of a multivariate model such as ARIMAX (Kongcharoen and Kruangpradit, 2013). Anggraeni, et al., (2017) compared the Vector Autoregressive (VAR) and ARIMAX models to forecast rice prices in Indonesia, finding that the ARIMAX model outperformed the VAR model by 15.27%, with a MAPE of 0.15%.

Recent advances in machine learning methods have significantly improved forecasting accuracy, especially for nonlinear datasets (Adetunji et al., 2022). These studies highlight that machine learning techniques often outperform traditional statistical models in time series forecasting. Support Vector Regression (SVR), a popular machine learning method, performs effectively with smaller datasets and complex relationships. It is a nonlinear extension of the Generalized Portrait algorithm, originally developed in Russia in the 1960s (Vapnik, 1998; Vapnik and Lerner, 1963; Vapnik and Chervonenkis, 1964). The modern form of Support Vector Machines (SVMs) was largely developed by Vapnik and colleagues at AT&T Bell Laboratories (Boser, Guyon, and Vapnik, 1992). Huang et al. (2005) applied SVMs to forecast financial movements using NIKKEI 225 index data, finding that SVMs demonstrated superior performance in financial forecasting. Using SVR modeling, Yang et al. (2022) conducted an air freight forecasting study in which the model outperformed other methods, achieving a Mean Absolute Percentage Error (MAPE) of less than 2.5%, along with the lowest Mean Absolute Error and Root Mean Square Error.

In contrast to SVR, the Gradient Boosting Regression Tree (GBRT) method is suitable for larger and more complex datasets, reducing prediction errors through a series of sequentially built trees (Friedman, 2001, 2002). In a study on flight delay prediction, Manna et al. (2017) demonstrated that the Gradient Boosted Decision Tree model achieved the highest R-squared values, with 92.3185% accuracy for arrival delays and 94.8523% for departure delays. Furthermore, Persson et al. (2017) applied the GBRT model to forecast future electricity production from rooftop PV installations.

Unlike GBRT and SVR, Random Forest operates with each tree running in parallel and independently. Introduced by Breiman, Random Forest is a widely used machine learning technique (Breiman, Friedman, Olshen, and Stone, 1984). In a study on cargo weight predictions for flights, Pinheiro (2021) employed various machine learning models, concluding that Random Forest achieved the best performance, with a Root Mean Square Error of 33%. Using Random Forest on a U.S. airline's arrival data, Rahul et al. (2022) predicted delay durations with an accuracy rate of 86%. Additionally, Adetunji et al. (2022) used Random Forest to forecast housing prices in Boston, achieving an acceptable prediction accuracy with an error margin of ±5%.

3. Design and Methodology

3.1. Data Set

The dataset for this study covers the years 2012–2023. Data on Turkey's air cargo tonnage, which serves as the dependent variable, were obtained from the General Directorate of State Airports Authority (DHMI). Among the independent variables, exchange rates in USD were collected from the Electronic Data Distribution System (EVDS) of the Central Bank of the Republic of Turkey. Crude oil purchase prices in USD were sourced from the U.S. Energy Information Administration, while GDP data were obtained from the Turkish Statistical Institute (TUIK). Since the predictive model is also implemented on a quarterly basis, a dataset comprising more than 30 time series observations is deemed sufficient (Gujarati, 2014).

3.2. Research Methodology

To forecast monthly air cargo tonnage, the Box-Jenkins methodology was employed using SARIMA and ARIMAX models. The best-fit parameters for these models were selected based on Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The final SARIMA model was determined as SARIMA (1,1,1) (0,1,1) [12] based on the lowest AIC score. While machine learning methods such as Random Forest, Gradient Boosting Regression Tree (GBRT), and Support Vector Regression (SVR) were also utilized. Eviews 12 software was used to determine and forecast SARIMA and ARIMAX models, while Python was employed for RF, GBRT, and SVR predictions.

3.2.1. SARIMA

SARIMA is formed by adding seasonal terms in the ARIMA models:

SARIMA (p, d, q)(P, D, Q)[S],

In the SARIMA model, p represents the non-seasonal autoregressive (AR) order, P denotes the seasonal autoregressive order, q is the non-seasonal moving average (MA) order, and Q indicates the seasonal moving average order. Meanwhile, d and D represent the overall differencing and seasonal differencing orders, respectively (Pepple and Harrison, 2017).

SARIMA(p,d,q)(P,D,Q)[S] models are written as (Pankratz, 1983);

$$\varphi_p(B)\phi_P(B^s)\nabla^d\nabla_s^D y_t = \theta_q(B)\Theta_Q(B^S)\mathrm{T}_t \quad (1)$$

∅ is the non-seasonal parameter of autoregression and θ is the non-seasonal parameter of moving average, φ is the seasonal parameter of autoregression and Θ is the seasonal parameter of moving average, ω is frequency and B is the diferential variable (Pepple and Harrison 2017).

3.2.2. ARIMAX

The ARIMAX model is an extension of the ARIMA model. This model incorporates additional independent variables, represented by the X at the end, which stands for "exogenous variables." This involves adding a separate exogenous variable to the model to aid in measuring the endogenous variable (Adu, Appiahene et al., 2023).

The ARIMAX (p,d,q) model consists of four main components (Almaleck, Massucco et al., 2024):

- An autoregressive component of order p,
- An order of differencing d,
- A moving average component q,
- A dataset comprising exogenous inputs.

The ARIMAX model equation is expressed as follows:

$$\Delta P_t = c + \beta X + \emptyset \Delta P_{t-1} + \theta_{1\epsilon_{t-1}} + \epsilon_t \quad (2)$$

Here, P_t and P_{t-1} represent the values in the current and previous periods, respectively. Similarly, ϵ_t and $\epsilon_{t-1}$are the error terms for these two periods. c denotes a constant term. $\emptyset_1$ and θ_1 indicate the influence of the previous period's value P_{t-1} and error ϵ_{t-1} in predicting the current value. $\beta$is a coefficient to be estimated based on model selection and data, and X is the exogenous variable of interest

The ARIMAX model is valuable as it integrates time series and regression components, allowing for a more comprehensive forecasting approach (Moslemi et al., 2024).

3.2.3. Random Forest

The Random Forest model is a widely used machine learning algorithm that reaches a single outcome by aggregating the outputs of multiple decision trees. Decision trees start with the most fundamental question and follow a series of questions, which form the decision nodes of the tree. Each question contributes to determining the final answer. In this structure, observations that meet certain criteria follow the "yes" branch, while those that do not meet these criteria follow an alternative branch. Decision trees use these questions to find the optimal method for training subsets and achieving the best results (Melzer, 2023).

The Random Forest equation is expressed as follows (Xing and Zhang, 2024):

$$F = S\big(T_1(d_1), T_2(d_2), \ldots, T_n(d_n)\big) \quad (3)$$

Here, F represents the final class, S denotes the selection function, T_n is the decision tree processing function, d_n represents the input data for each decision tree, and n is the number of decision trees. Based on these functions, the corresponding Random Forest prediction model can be constructed.

3.2.4. Support vector regression (SVR)

Support Vector Regression (SVR) is one of the most important branches of Support Vector Machines (SVMs). The classical regression model constructs the loss function by calculating the difference between the actual value and the predicted value. For continuous-valued functions, the mathematical representation can be simplified by incorporating the x value into the w vector and adding b for multidimensional data, as shown in Equation 1. This results in a multivariate regression, illustrated in Equation 1.2 (Awad et al., 2015).

Equation 1:

$$y = f(x) =< w, x > +b = \sum_{j=!}^{M} w_j\, x_j + b, y, b \in R, x, w \in R^m \quad (4)$$

Equation 1.2 (Multivariate Regression):

$$f(x)[{}^{w^T}_{b}[{}^{x}_{l} = w^{Tx} + b\ x, w \in R^{M+1}] \quad (5)$$

3.2.5. Gradient boosting regression tree

A decision tree is a predictive model proposed by Quinlan (1986). As illustrated in Figure 1, a decision tree is a type of binary tree where each node represents a test of an attribute, and the leaves indicate the predicted value. When the target variable has a continuous real value (typically represented by real numbers), the decision tree is referred to as a regression tree.

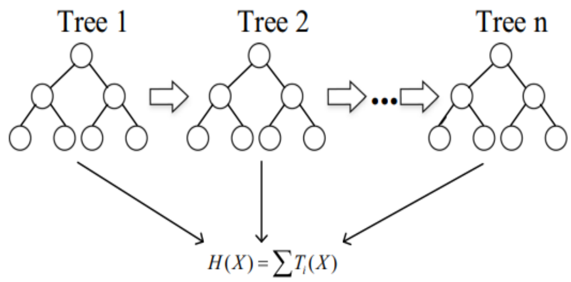

Figure 1. A GBRT (Gradient Boosting Regression Tree) model. Source: Huang et al. 2019

Each tree within the model is a decision tree, and the t_i tree is built sequentially after the t_(i-1) tree. The predicted value of the GBRT model is the sum of the values predicted by each individual tree. The target input value for the t_i tree is the residual between the current predicted value and the true target value, defined as:

$$input_i = \sum_{j=1}^{i-1} T_j - y_{true} \quad (6)$$

Where T_j denotes the prediction result of the jjj-th decision tree $1 \leq j \leq i-1$and y_{true} is the true target value of the examples.

3.2.6. Evaluating the Predictive Power of the Model

After identifying the appropriate forecasting model, it is essential to conduct forecast evaluation tests to assess the model's predictive capability for future projections. If the predictive accuracy of the selected model does not meet the desired level of statistical significance in these tests, it should not be used for future forecasting. In the study, forecasted and actual passenger numbers, along with the error margins for each of the various models, are presented for evaluation.

To identify outliers, residual distribution graphs, bias, and covariance values are utilized. To measure the accuracy of the forecasts and to determine the predictive power of the model, Mean Absolute Percentage Error (MAPE) and the Theil Inequality Coefficient are employed. According to Lewis (1982), models with a MAPE value below 10% are classified as very good, those between 10–20% as good, those between 20–50% as acceptable, and those above 50% as inaccurate or erroneous. Additionally, the Theil coefficient is expected to be close to zero (Vergil & Özkan, 2007). This coefficient is divided into three components: the "Bias" proportion, which represents systematic error, with values closer to zero indicating higher reliability in forecast results. The second component, the covariance proportion, reflects unsystematic error; a larger value compared to other components indicates the error is unsystematic (Bozkurt, 2013:186). The covariance proportion represents the variability in the model that arises beyond our control, helping to explain external influences on forecast error.

3.2.7. Structuring the Forecasting Strategy

Static and dynamic forecasting are utilized in the comprehensive evaluation of statistical and machine learning models. Static forecasting refers to cases where the model's structure and parameters remain fixed once the training and testing datasets are defined. In contrast, dynamic forecasting is more complex, as the model's structure and parameters are recalibrated whenever new observations are introduced. Therefore, in dynamic forecasting, the training data are updated after each forecast by adding the most recent observation.

In this study, the independent variables used include GDP, exchange rate, and Brent crude oil prices, all of which are factors influencing airline cargo tonnage (Tuncer & Aydoğan, 2019; Totamane et al., 2009).

4. Findings

4.1. Descriptive Statistics

The graphical representation of data for the relevant series is provided in Figure 2. As illustrated in Figure 2, airline cargo tonnage increased from 2012 until 2020, experienced a decline in 2020 and 2021 due to the pandemic, and then resumed an upward trend in 2022. Additionally, demand demonstrates seasonal fluctuations. Crude oil purchase prices exhibit a volatile pattern, while GDP has shown a rising trend following a decline observed from 2012. Furthermore, the USD/TRY exchange rate has been on an upward trajectory since 2018. Descriptive statistics for the series are presented below in Table 1.

4.2. Descriptive Statistics

As shown in Table 1, the Jarque-Bera test results indicate that, at the 95% significance level, the probability values for Airline Cargo Tonnage (Ton) and Brent are greater than 0.05 ($p > 0.05$). Therefore, these series can be considered normally distributed. However, the probability values for Gross Domestic Product (GDP) and Exchange Rate are 0.00002 and 0.0, respectively, indicating statistical significance at the 95% level ($p < 0.05$). Thus, the null hypothesis H_0 is rejected for these series, suggesting that they do not follow a normal distribution. To address this, logarithmic transformations were applied to these series, and the corresponding results are presented in Table 2.

Table 1. Descriptive Statistics

Statistic	Ton	GDP	Exchange Rate	Brent
Mean	281071.2	7.27E+10	6.764236	75.04694
Median	275582.0	7.23E+10	3.815000	71.71500
Maximum	484194.0	9.42E+10	29.07000	125.4500
Minimum	87953.00	6.00E+10	1.760000	18.38000
Std.Dev.	83161.89	8.69E+09	6.489477	25.56991
Skewness	0.335005	0.929005	1.768739	0.177831
Kurtosis	2.758974	3.934021	5.387848	1.933500
Jarque-Bera	3.042042	25.94757	109.2934	7.583511
Probabilty	0.218489	0.00002	0.00000	0.052556
Sum	40474253	1.05E+13	974.0500	10806.76
Sum Sq.Dev.	9.89E+11	1.06E+22	6022.203	93693.85
Observation	144	144	144	144

According to the Jarque-Bera test results following the logarithmic transformation of the series, the probability values for the LGDP and Exchange Rate series are 0.07 and 0.06, respectively ($p > 0.05$). This indicates that these series have also been adjusted to conform to a normal distribution.

Table 2. Log (Exchangre Rate, GDP)

Statistic	Exchange Rate	GDP
Mean	1.561783	2.500.257
Median	1.338899	2.500.455
Maximum	3.369707	2.526.833
Minimum	0.565314	2.481.803
Std.Dev.	0.79861	0.114053
Skewness	0.615611	0.581266
Kurtosis	2.327863	3.352372
Jarque-Bera	11.80607	8.853872
Probabilty	0.072132	0.067322
Sum	974.0500	3.600.371
Sum Sq.Dev.	6022.203	1.860.155
Observation	144	144

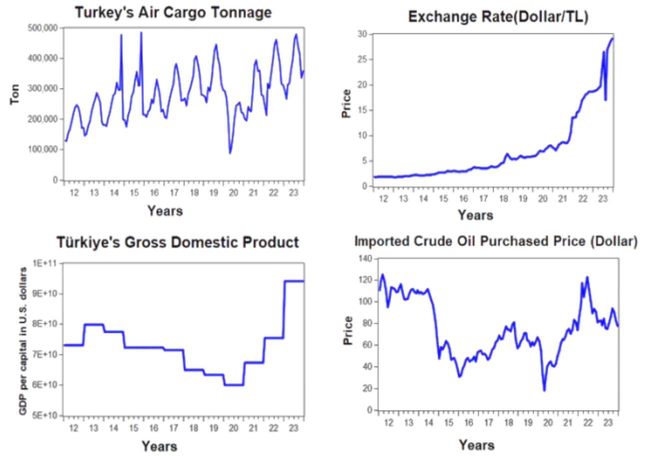

Figure 2. Graphical Representation of the Series (Monthly Periods for the 2012-2023 Period)

4.2. Forecasting performance of statistical models

The forecast performance of the two statistical models is presented in Table 3. Prediction performance has been evaluated using seven metrics, with the best results highlighted in bold.

The results according to forecasting strategies are divided into six sections and presented in Table 3. Each section consists of two statistical models and seven evaluation metrics. The forecast performances of the static and dynamic strategies have been analyzed and compared.

In the static analysis, examining short-term forecasts (1-step and 5-step), the SARIMA model provides more accurate predictions with lower MAE and MAPE values, indicating better absolute error rates. This finding suggests that the SARIMA model performs better in the short term. In contrast, for long-term forecasts (10-step), the ARIMAX model demonstrates a more balanced and consistent performance with lower RMSE, MAE, and Theil's U values, indicating a lower overall error rate. This result shows that the ARIMAX model outperforms the SARIMA model in long-term forecasting, providing more reliable outcomes. In conclusion, the SARIMA model produces more accurate predictions for short-term forecasts, while the ARIMAX model performs better in terms of overall error rates for long-term forecasts. This finding suggests that the SARIMA model should be preferred for short-term projections, whereas the ARIMAX model is more suitable for long-term projections.

The findings from the dynamic analysis indicate that the ARIMAX model provides lower values for critical metrics such as RMSE, MAE, and Theil's U in short-term (1-step), medium-term (5-step), and long-term (10-step) forecasts, which measure error rates. These results demonstrate that the overall predictive accuracy of the ARIMAX model is higher than that of the SARIMA model. Specifically, ARIMAX exhibits lower RMSE and MAE values across all forecast steps, indicating superior error performance. Additionally, the ARIMAX model's superiority in terms of MAPE and Theil's U values suggests that it offers not only better absolute error rates but also a more balanced and reliable forecast in terms of relative error performance. Consequently, the data indicate that the ARIMAX model is a stronger choice for dynamic forecasting, suitable for both short- and long-term predictions. In conclusion, the comparison of static and dynamic analyses reveals that the lower error rates of the static SARIMA model indicate its reliability and consistency in short-term forecasting. However, in long-term (10-step) forecasts, the ARIMAX model demonstrates lower RMSE and Theil's U values in both static and dynamic forecasts, providing a more balanced forecast in terms of overall error performance. Notably, static ARIMAX forecasts yield the best performance over the long term, marked by lower error rates. This finding suggests that the static ARIMAX model is more suitable for long-term forecasting.

4.3. Forecasting performance of statistical models

In the machine learning comparison in Table 4, the Random Forest model exhibited the lowest RMSE, MAE, and MAPE values in both static and dynamic forecasts, along with the lowest bias (BIAS) rate. This result indicates that the Random Forest model offers greater reliability in both short- and long-term forecasts compared to other models. On the other hand, The Support Vector Regression (SVR) model demonstrated weaker predictive performance compared to other machine learning models, particularly in long-term forecasts. This outcome can be attributed to SVR's sensitivity to noise in time series data and its limitations in capturing nonlinear trends effectively. Unlike tree-based models such as Random Forest and Gradient Boosting, which can handle complex interactions between variables, SVR relies on a kernel-based transformation, making it less robust for highly volatile air cargo data. The Gradient Boosting Regression Tree (GBRT) model showed moderate performance, generally demonstrating higher error rates and thus offering limited reliability.

Overall, the Random Forest model stands out as the most suitable machine learning method in terms of forecast reliability. Notably, for 5-month forecast periods, the GBRT model produced the best results. Consequently, the superior performance of Random Forest in both short- and long-term forecasts makes it the most preferred model among forecasting methods. Furthermore, when comparing static and dynamic forecasts of the Random Forest model, the dynamic method yielded the best results across 1-step, 5-step, and 10-step forecasts.

4.4. Comparison of Machine Learning and Statistical Methods

In machine learning methods, the best results were achieved with the dynamic approach. In statistical methods, the SARIMA model provided the most accurate results for short-term forecasts (1-step and 5-step), while the ARIMAX model performed best for long-term forecasts (10-step). A comparison of these models revealed that Random Forest yielded the highest accuracy in 1-step, 5-step, and 10-step forecasts.

Given the superior performance of the Random Forest analysis in both short- and long-term forecasts, a projection graph for 2024-2025 is presented in Figure 3. The model's forecast for total airline cargo in 2024 is 4,675,000 tons, while the estimate for 2025 is 4,690,000 tons. Considering the airline cargo tonnage in 2023 was 4,163,142 tons, a 12% increase is projected for 2024, followed by a 1% increase for 2025 compared to the previous year.

Table 3. Forecasting performance of two statistical models

				Static				
	1-step ahead			**5-step ahead**			**10-step ahead**	
SARIMA	RMSE	**45532.3**	**SARIMA**	RMSE	**45532.3**	**SARIMA**	RMSE	45532.3
	MAE	**28712.19**		MAE	**28712.19**		MAE	32121.2
	MAPE	**11.31**		MAPE	**11.314**		MAPE	11.314
	BIAS	**0.001105**		BIAS	**0.0011**		BIAS	0.001
	VARIANCE	**0.08**		VARIANCE	**0.0804**		VARIANCE	0.08
	COVARIANCE	**0.91**		COVARIANCE	**0.9184**		COVARIANCE	0.918
	THEIL	**0.07**		THEIL	**0.077**		THEIL	0.077
ARIMAX	RMSE	44837.5	**ARIMAX**	RMSE	44837.5	**ARIMAX**	RMSE	**44837.5**
	MAE	30319.34		MAE	30319.4		MAE	**30319.34**
	MAPE	12.24		MAPE	12.248		MAPE	**12.482**
	BIAS	0		BIAS	0		BIAS	**0**
	VARIANCE	0.09		VARIANCE	0.096		VARIANCE	**0.0963**
	COVARIANCE	0.9		COVARIANCE	0.9		COVARIANCE	**0.903**
	THEIL	0.07		THEIL	0.076		THEIL	**0.077**
				Dynamic				
	1-step ahead			**5-step ahead**			**10-step ahead**	
SARIMA	RMSE	79556.89	**SARIMA**	RMSE	79556	**SARIMA**	RMSE	79556.89
	MAE	62985.49		MAE	62985.49		MAE	62985.49
	MAPE	2.460.376		MAPE	2.460.376		MAPE	2.460.376
	BIAS	0.004		BIAS	0.004		BIAS	0.004
	VARIANCE	0.808		VARIANCE	0.808		VARIANCE	0.808
	COVARIANCE	0.18		COVARIANCE	0.186		COVARIANCE	0.186
	THEIL	0.13		THEIL	0.13		THEIL	0.138
ARIMAX	RMSE	**69490.7**	**ARIMAX**	RMSE	**69490.7**	**ARIMAX**	RMSE	**44837.5**
	MAE	**54202.93**		MAE	**54202.93**		MAE	**30319.34**
	MAPE	**212.932**		MAPE	**21.293**		MAPE	**12.24**
	BIAS	**0.0016**		BIAS	**0.001**		BIAS	**0**
	VARIANCE	**0.4155**		VARIANCE	**0.4155**		VARIANCE	**0.096**
	COVARIANCE	**0.582**		COVARIANCE	**0.5827**		COVARIANCE	**0.903**
	THEIL	**0.12**		THEIL	**0.1203**		THEIL	**0.076**

Table.4 Forecasting performance of two statistical models

				Static				
	1-step ahead			**5-step ahead**			**10-step ahead**	
RF	RMSE	**8553.4**	**RF**	RMSE	**24293.66**	**RF**	RMSE	**38184.05**
	MAE	**8553.4**		MAE	**22698.45**		MAE	**34345.93**
	MAPE	**2.35**		MAPE	**7.88**		MAPE	**14.02**
	BIAS	**0.0005**		BIAS	**4.61**		BIAS	**0.000**
	VARIANCE			VARIANCE	**0.99**		VARIANCE	**0.65**
	COVARIANCE			COVARIANCE	**0.58**		COVARIANCE	**0.47**
	THEIL	**0.012**		THEIL	**0.04**		THEIL	**0.09**
SVR	RMSE	86951.8	**SVR**	RMSE	60506.75	**SVR**	RMSE	60506.75
	MAE	86951.88		MAE	42024.14		MAE	44024.14
	MAPE	24.11		MAPE	9.016		MAPE	18.031
	BIAS	0.058		BIAS	0.008		BIAS	0.992
	VARIANCE			VARIANCE	1.914		VARIANCE	7.1964
	COVARIANCE			COVARIANCE	1.773		COVARIANCE	1.1935
	THEIL	0.137		THEIL	0.074		THEIL	0.10636
GBR	RMSE	20574.42	**GBR**	RMSE	26052.112	**GBR**	RMSE	37652.818
	MAE	20574.42		MAE	25444.459		MAE	33477.928
	MAPE	5.70		MAPE	8.523		MAPE	135.319
	BIAS	0.032		BIAS	0.0007		BIAS	0.0001
	VARIANCE			VARIANCE	0.714		VARIANCE	0.465
	COVARIANCE			COVARIANCE	0.648		COVARIANCE	0.064
	THEIL	0.029		THEIL	0.043		THEIL	0.0644
				Dynamic				
	1-step ahead			**5-step ahead**			**10-step ahead**	
RF	RMSE	**8553.4**	**RF**	RMSE	20860.00	**RF**	RMSE	**38464.43**
	MAE	**8553.4**		MAE	18626.868		MAE	**30979.42**
	MAPE	**2.37**		MAPE	6.482		MAPE	**13.318**
	BIAS	**0.000**		BIAS	0.000		BIAS	**0.000**
	VARIANCE			VARIANCE	0.89		VARIANCE	**0.458**
	COVARIANCE			COVARIANCE	0.40		COVARIANCE	**0.470**
	THEIL	**0.012**		THEIL	0.034		THEIL	**0.064**
SVR	RMSE	86951.885	**SVR**	RMSE	42957.747	**SVR**	RMSE	60542.591
	MAE	86951.885		MAE	29828.977		MAE	44049.188
	MAPE	24.119		MAPE	8.988		MAPE	18.049
	BIAS	0.058		BIAS	0.008		BIAS	0.002
	VARIANCE			VARIANCE	1.966		VARIANCE	3.480
	COVARIANCE			COVARIANCE	0.193		COVARIANCE	1.189
	THEIL	0.1371		THEIL	0.074		THEIL	0.106
GBR	RMSE	20574.427	**GBR**	RMSE	**16703.041**	**GBR**	RMSE	44917.485
	MAE	20574.427		MAE	**15484.229**		MAE	32583.513
	MAPE	5.707		MAPE	**5.156**		MAPE	14.368
	BIAS	0.003		BIAS	**3.360**		BIAS	0.0002
	VARIANCE			VARIANCE	**0.333**		VARIANCE	0.209
	COVARIANCE			COVARIANCE	**0.136**		COVARIANCE	0.636
	THEIL	0.029		THEIL	**0.027**		THEIL	0.076

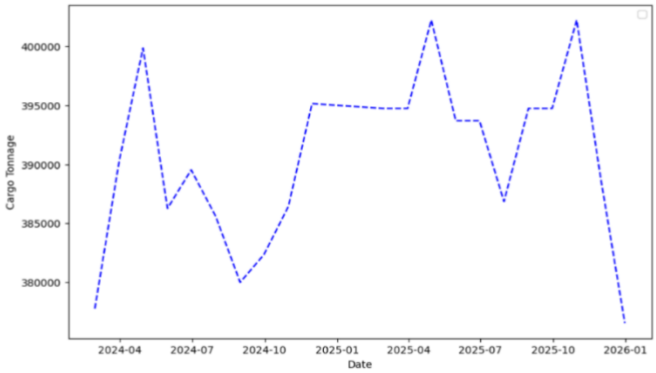

Figure 3. Random Forest Forecast of Airline Cargo for 2024-2025

5. Conclusion

In order to provide reliable forecasts of future air cargo tonnage in air cargo logistics, five different forecasting models were used to evaluate the advantages and disadvantages of statistical and machine learning-based forecasting approaches. To enable a more comprehensive comparison, various scenarios were developed by applying two distinct forecasting strategies—static and dynamic—across three forecasting periods.

Stationarity tests were conducted on the airline cargo tonnage series, used as the dependent variable, and on the independent variables: Gross Domestic Product (GDP), Brent oil prices, and exchange rate (Currency). According to the Jarque-Bera test results, the probability values for the Airline Cargo Tonnage (Ton) and Brent series were found to be significant at the 95% confidence level ($p > 0.05$), indicating that these series are normally distributed. For the Currency and GDP series, a logarithmic transformation was applied, after which the Jarque-Bera test confirmed that these series also conformed to a normal distribution.

Overall, the results indicate that machine learning-based models generally perform better with time series data. Specifically, the Random Forest model achieved the highest predictive accuracy across 1- to 10-month periods, as evidenced by its lower RMSE, MAE, and MAPE values compared to other models. The Gradient Boosting Regressor (GBR) outperformed other methods in 5-month forecasts, whereas SARIMA demonstrated strong competitiveness in short-term predictions. These findings suggest that Random Forest's ability to handle nonlinear patterns and interactions between multiple influencing factors makes it particularly suitable for air cargo forecasting. Furthermore, the superior performance of dynamic modeling strategies highlights the potential of machine learning methods in improving forecasting reliability over traditional statistical approaches.

The Random Forest forecast for the next two years predicts a 12% increase in 2024 and a 1% increase in 2025 compared to the previous year. Considering that air cargo volumes are influenced by numerous factors and long-term variables, future studies will focus on developing more advanced and sophisticated forecasting techniques that incorporate additional variables cited in the literature alongside those used in this model.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Bibliometric Analysis of Studies on Artificial Intelligence in the Air Transportation Sector

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Abstract

The use of artificial intelligence is becoming widespread in almost all sectors. The air transportation sector is naturally where artificial intelligence studies are frequently carried out. In both the application process and academic studies, studies on artificial intelligence have increased significantly in recent years. It is thought that examining the studies conducted in this context will contribute to the understanding of the existing literature on artificial intelligence and help predict the trends that will emerge in the future. For these reasons, this study aims to conduct a bibliometric analysis of studies on artificial intelligence in the air transportation sector. The analysis of 1712 academic studies obtained from the Scopus database was conducted with R Bibliometix and VOSViewer software. In the study, analyses such as the authors and countries with the highest number of publications, the most influential authors and countries, the institutions that contribute the most to the studies, the most influential journals, thematic analysis, co-occurrence, co-citation, and bibliographic coupling analysis were performed. As a result of the analysis, it was determined that most of the studies are from the Asian region, and the rate of cooperation in the studies is high, but the rate of international cooperation is relatively low. On the other hand, it was revealed that the motor themes in studies on artificial intelligence are air traffic control, Unmanned Aerial Vehicle, optimization, eye tracking, and automation, while the basic themes are machine learning, deep learning, aviation safety, neural network, and situation awareness.

1. Introduction

Academic studies on artificial intelligence (AI) date back to the 1960s. The article “Bibliography on Simulation, Gaming, Artificial Intelligence, and Allied Topics” written by Shubik in 1960 and published in the Journal of the American Statistical Association provides a bibliography of topics such as simulation, gaming, and AI (Shubik, 1960). Following this study, it is seen that many studies on AI have been carried out in the literature. When the keyword “Artificial Intelligence” is searched in the Scopus database, it is seen that approximately 580,000 articles have been published. When the distribution of the published articles by year is analyzed, it can be mentioned that the number of studies on AI in 1984-1985 doubled compared to the previous years. This situation is not surprising. Indeed, the 1980s can be seen as the year when internet technology started to become widespread (Leiner et al., 1997). The fact that data silos on the Internet contain the data necessary for the processing of AI and algorithms (O'Neill et al., 2023) has led to an increase in the number of studies on AI.

In literature, it is possible to encounter very different definitions of what AI is. This is because AI has a definition specific to each field where it is used. This makes it difficult to answer the question of what AI is. If a general definition is desired; AI can be defined not as a technology or a set of technologies, but as an ever-evolving limit of emerging computing capabilities (Berente et al., 2021). In another definition, AI refers to the ability of a machine to communicate, reason, and operate independently in a human-like manner when faced with both familiar and novel situations (Du-Harpur et al., 2020). Although AI is doing great things today, humanity's expectations for AI are much higher. In the future, it seems inevitable that AI will become one of the routines of our daily lives.

AI has different applications in many sectors. However, it is very important to show them in a certain typology to understand where AI has come from. In this context, AI has become frequently used in object recognition and perception, predictive maintenance, gesture and speech recognition, robotic surgery, medical applications, military robotics, agriculture, service robotics, autonomous driving, and robotic manufacturing (Soori et al., 2023).

When the literature on AI is examined, it is seen that research has been carried out in many fields of science. Among these fields of science, it is seen that most studies are carried out in the fields of computer science, engineering, mathematics, and medical sciences, respectively (Scopus, 2024). However, in addition to these fields of science, social sciences, physics and astronomy, decision sciences, material sciences, biochemistry, genetics and molecular biology, business, management and accounting, energy, environmental sciences, arts and humanities, earth and planetary sciences, chemical engineering, economics and finance, chemistry, neuroscience, agricultural and biological sciences, health professions, psychology, pharmacy, pharmacology and toxicology, immunology and microbiology, nursing, veterinary medicine and dentistry (Scopus, 2024).

The studies carried out in the mentioned fields of science are carried out in a widespread framework that concerns human life, from measuring the academic performance of students in the field of education (Haron et al., 2025) to the use of AI for the diagnosis of cancer disease in the field of medicine (Nivedhitha et al., 2024). However, it is almost impossible not to get lost in literature since the field of study on AI is so wide and it is one of the most popular topics of the last period. In this context, it would be useful for researchers to draw a framework of how the literature has been shaped in the past, how it has developed, and where it will evolve in the future. While it is impossible to draw such a framework for all studies on AI, it is also unnecessary. Instead, drawing sector or subject-based frameworks will contribute more to the relevant research field. With this in mind, this study aims to draw a framework for studies on AI in the air transportation sector.

The air transportation sector is seen as a sector that has serious impacts on the economic and social development of countries (Raihan et al., 2024). According to the Air Transport Action Group (ATAG), the contribution of the air transportation sector to the global economy amounted to $3.5 trillion in 2019 (ATAG, 2020). That year, the air transport sector contributed to creating 11.3 million direct, 18.1 million indirect, and 13.5 million induced jobs worldwide (ATAG, 2020). On the other hand, the air transportation sector also has significant impacts on the development of other sectors. For example, the air transportation sector is closely linked to the tourism sector. Both sectors feed each other and coexist together (Bieger & Wittmer, 2006; Forsyth, 2016). While the presence of tourism destinations increases the number of airline passengers, the opening of new destinations through air transportation increases the number of tourists. According to (Putrik et al., 2022), more than half of international tourism activities are realized through air transportation. According to ATAG data, the air transportation sector has a catalytic effect on the creation of around 45 million new jobs in the tourism sector (ATAG, 2020). The fact that the air transportation sector both transports more tourists and contributes to the creation of new business areas in the field of tourism is quite remarkable in terms of economic and social development. It would be wrong to talk only about the impact of the sector on the tourism sector. The development and sustainability of international trade is also one of the positive externalities of the air transport sector. For example, although 1% of global cargo transportation is carried by air cargo, approximately 6.5 trillion dollars' worth of cargo was transported by air cargo in 2019 (ATAG, 2020). This value is equal to approximately one-third of total cargo transportation activities. The reason why the cargo volume is low, but the revenue generated is high is due to the high unit value of the products transported by air cargo. The speed benefit of air cargo also contributes to the smooth continuation of daily production (such as fast delivery of machinery and equipment). On the other hand, it is of course possible for products that can spoil quickly (flowers, food, vaccines, etc.) to take place in world markets by air cargo. As can be seen, the air transportation sector has serious social and economic impacts both globally and on the development of countries. In this context, it is thought that studies on the air transportation sector should be carefully examined.

In the air transportation sector, which is one of the leading sectors in terms of technological advances, it is not surprising that AI applications are rapidly adapted to the processes. However, the air transportation sector involves many different disciplines. While the sector is in the field of science in terms of technical issues such as aircraft production, aircraft maintenance, and air traffic management, it is in the field of social sciences in terms of airport management, airline management, and ground handling management. On the technical side, topics such as aerodynamics (Cao et al., 2014; Lynch & Khodadoust, 2001), fuel (Daggett et al., 2006), engine technology (Bewlay et al., 2016; Pollock, 2016), and materials science (Kumar & Padture, 2018; Parveez et al., 2022) are frequently studied, while on the social science side, topics such as service marketing (Marina et al., 2016; Park et al., 2020), passenger satisfaction (Bakır et al., 2022), culture (Quick, 1992; Yayla-Kullu et al., 2015) are frequently studied. On the other hand, topics such as optimization (Deng et al., 2022; García et al., 2005), ergonomics and human factors (Arcúrio et al., 2018; Brown et al., 2023), safety (Kayhan et al., 2018; Tamasi & Demichela, 2011) and security (Bağan & Gerede, 2019; Stroeve et al., 2022), which need to be studied both technically and socially, are also frequently studied in the air transport sector. In this context, it is considered that studies on AI may have emerged under very different topics. In the light of the aforementioned, the research questions of this study are formulated as follows;

1. What is the level of development of academic AI studies for the air transportation sector?

2. Which countries and researchers focus on which topics for the concept of AI in the air transportation sector?

3. Which topics are trending in AI studies in the air transportation sector?

To answer the research questions, the study is structured as follows. Section 2 reviews previous studies on AI in the air transportation sector. Section 3 provides information on the methodology of the study, and Section 4 presents the results of the study. Finally, Section 5 discusses the findings of the study, makes predictions for future studies, and concludes the study.

2. Literature Review

A literature review was conducted to understand the studies on AI applications in the field of aviation. For a better understanding of the subject, it would be a more accurate approach to consider the studies under two headings: technical sciences and social sciences studies.

It is possible to mention that the number of studies in the field of social sciences in studies on AI in air transportation is less than the number of technical studies. However, there are still many studies in the field of social sciences in literature. For example, some studies utilize deep learning and artificial neural networks in studies carried out to prevent fraudulent practices in airline ticketing (Aras & Guvensan, 2023). In studies within the scope of social sciences, AI is mostly used to investigate passenger demand for airline companies. In the study of Srisaeng et al. (2015), artificial neural networks were used for demand forecasting for low-cost carriers, in the study of Wan et al. (2020), the long-short-term memory technique was used, and in the study of Jin et al. (2020), kernelized extreme learning machine method was used. Demand forecasts were carried out not only for airlines but also for businesses that do not exist but are expected to operate for urban air mobility (Rajendran et al., 2021). On the other hand, airports also emerge as another demand forecasting component. In the study of Koçak (2023), deep learning method was used to investigate airport passenger demand.

Another topic examined in social science studies on the use of AI in air transportation is passenger profiling. Zheng et al.'s (2016) study used deep neural networks to identify disruptive passengers, while Gu et al. (2020) study used back-propagation neural networks to identify the root causes of passengers' disruptive behavior due to airport delays. Similarly, Koshekov et al. (2021) study used deep learning for more successful passenger profiling.

Another area of use of AI is customer loyalty. While Chanpariyavatevong et al. (2021) used Bayesian networks to create customer loyalty in airline companies, Yao et al. (2022) used genetic algorithms to predict the next flights of frequent flyers. On the other hand, some studies used deep learning-supported Gated Recurrent Unit to predict airline ticket prices (Degife & Lin, 2023). Chin et al. (2023) used machine learning methods to predict no-show passengers in airline operations. Ouf (2023) used a deep learning method to improve airline service quality and increase passenger satisfaction.

Chouraqui and Doniat (2003) and Q. Li et al. (2023) used machine learning and AI applications to detect pilot errors, in other words, human factors. In another study on human factors, deep supervised active learning, artificial neural networks, and random forest models were used to determine the effect of human factors on aircraft accidents (Nogueira et al., 2023).

One of the topics addressed in AI studies in aviation is related to situational awareness. In the study of Khazab et al. (2013), multi-agent systems were examined to increase situational awareness, in the study of Kilingaru et al. (2013), a rule-based system was examined, in the study of Ramos et al. (2023), a decision support system was aimed to be developed with the Integrated Flight Advisory System (IFAS) using AI. In the study of Thatcher (2014), the use of AI to determine the situational awareness of student pilots was examined. In the study of Gomolka et al. (2022), a deep neural network approach was used with eye tracking to record and analyze the attention of pilots, and in the study of Taheri Gorji et al. (2023), machine learning was used to distinguish the cognitive workloads of pilots during the flight.

Another topic related to AI in aviation is the reporting of incidents affecting aviation safety. Accurate and unbiased reporting is critical to preventing future unsafe incidents. For example, Oza et al. (2009) developed a decision support system to classify reports of incidents affecting aviation safety and health, Wang et al. (2016) developed a concurrency network-based algorithm to increase the accuracy of classifying reports, and Abedin et al. (2010) investigated learning-based algorithms to improve reporting systems and improve labeling used in reports. Hsiao et al. (2013) used artificial neural networks to analyze safety reporting, Jin et al. (2021) and Zhang et al. (2021) used a sequential deep learning technique to classify safety incidents, and Madeira et al. (2021) used machine learning method to identify human factor categories in aircraft accident reports.

Another group of studies examined in AI studies consists of studies conducted to increase aviation safety. For example, in the study of Bareither and Luxhøj (2007), Bayesian belief networks were used to determine aircraft accident cases and accident antecedents and to increase flight safety by reducing the potential risks of certain types of accidents. In the study of Mohaghegh et al. (2009), a hybrid model was created using Bayesian belief networks and an attempt was made to determine organizational factors in aircraft maintenance activities. In the study of Xiaomei et al. (2019), a deep neural network model was used to estimate the aviation risk index, while in the study of Zhang and Mahadevan (2021), Bayesian network modeling was used to determine the causal relationships of airline accidents.

When studies on AI in air transportation are examined, it is seen that many studies have been conducted in the field of technical sciences. These studies have been carried out in a wide variety of fields. Among these fields, topics such as material production, design, engineering, aircraft maintenance, and air traffic stand out. For example, in the study of Huang et al. (2003), artificial neural networks and genetic algorithms were used in the shaping of sheet metals used in aircraft, and in the study of Qiu et al. (2016), a genetic algorithm that makes compliance estimation was used in the design of a device used to reduce vibrations. In the study of Ernst and Weigold (2021), machine learning and AI approaches were used in the design of compressor blades used in aircraft engines, and in the study of Meister et al. (2021), the use of AI applications to increase the efficiency of the production processes of composite materials used in aircraft was investigated. Similarly, Djavadifar et al. (2022) used a deep convolutional neural network model to detect boundaries and defects in composite materials. Lu et al. (2006) used artificial neural networks in helicopter design, Moon et al. (2014) a deliberate particle swarm optimization approach for the design of aircraft platforms, Morris et al. (2016) used AI to ensure the silence of Unmanned Aerial Vehicles (UAVs), Secco and Mattos (2017) artificial neural networks to predict aircraft aerodynamic coefficients, Yu et al., 2018) a particle swarm optimization algorithm was used for the development of electrohydrostatic actuators. Baklacioglu et al. (2018) used artificial neural networks and hybrid genetic algorithms to calculate the energy sustainability of business jets, Okpoti et al. (2019) a Lagrangian-based algorithm was used to design a universal electric motor for general aviation aircraft. Xu et al. (2019) used deep neural networks and reinforcement learning techniques in the development of UAVs, Jiao et al. (2023) used reinforcement learning to improve the safety and efficiency of anti-skid system, and Ghienne and Limare (2023) used machine learning to measure structural stress during flight.

Another area of use of AI in technical sciences in air transportation is related to aviation security. In the study of Singh et al. (2004), learning algorithms were used to improve x-rays used in airport screening processes, in the studies of Kim et al. (2020) and Su et al. (2023), deep learning and artificial neural networks were used to detect objects that could breach security in screening processes. In the study of Koroniotis et al. (2020), AI-supported cyber defense techniques were examined to ensure the cyber security of smart airport systems.

Another issue addressed in studies on the use of AI in air transportation is the detection of errors in air-ground communication. For example, in the study of Ragnarsdottir et al. (2006), errors in communication between pilots and Air Traffic Control (ATC) were tried to be minimized with language technology. Similarly, in the study of Guimin et al. (2018), errors in air-ground communication were tried to be eliminated with deep learning.

The field of technical sciences where most AI studies are conducted is the air traffic component. Issues such as the complex structure of air traffic, the emergence of conflicts, and the fact that the human factor is very decisive in this area lead to increased academic studies on AI in air traffic. For example, graph-based algorithms were used in the study of Li et al. (2010). In the study of Cruciol et al. (2015), multi-agent systems were used for a more successful air traffic flow. In the study of Ghoneim and Abbass (2016), the minimum separation distances between aircraft were estimated using an optimization algorithm. In the study of Cai et al. (2017), a route and time slot assignment algorithm were used, in the study of Chen et al. (2017), a chance-based model using an integer programming optimization model was used, and in the study of Xiao et al. (2018), a hybrid indirect and direct genetic algorithm was developed. Lin et al. (2019) and Liu et al. (2019) discuss trainable deep-learning methods to improve air traffic flow prediction accuracy and stability. Another topic addressed in studies on air traffic is related to conflicts. In the study of Casado and Bermúdez (2020), artificial neural networks are used to detect and resolve conflicts between aircraft during the final approach, while in the study of Tran et al. (2020), an AI digital assistant solution is proposed to contribute to the resolution of conflicts between airspace users.

AI studies also include studies on air traffic controllers. In the study of Shen and Wei (2021), deep learning methods were used to detect the fatigue of air traffic controllers, while in the study of Pham et al. (2020), machine learning techniques were used to increase the success of air traffic planning controllers. Another topic addressed in AI studies on air traffic is the reduction of air traffic complexity and the detection of anomalies. One of the topics addressed in AI studies on air traffic is the reduction of air traffic complexity and the detection of anomalies. Machine learning was used to reduce complexity in the study of Rehman (2021), and a hyperheuristic framework based on reinforcement learning was used in the study of Juntama et al. (2022). In the study of De Riberolles et al. (2022), industrial control systems based on deep learning were examined for anomaly detection, and an explainable semi-supervised deep learning model was used in the study of Memarzadeh et al. (2022). In Xu et al. (2023), Bayesian ensemble graph attention network is used to predict air traffic density, while in the study of Shijin et al. (2016), an adaptive ant colony algorithm is used to optimize air route networks. Finally, in the study of Kistan et al. (2018), the requirements, certification processes, and acceptance processes for the use of AI in air traffic systems are investigated.

Another topic addressed in studies on AI applications in aviation is the detection of terrain and obstacles on the terrain. Gandhi et al. (2006) developed a learning algorithm for obstacle detection, Zhao et al. (2017) used a mixed integer linear programming method based on hemisphere matching and horizon control, Kang et al. (2008) investigated the use of artificial neural networks for terrain detection of UAVs, and Kamiya (2010) investigated a system that detects and warns about changes in the airport environment with AI.

Another topic addressed in AI-related studies is aircraft trajectories. In the study of Fallast and Messnarz (2017), a random tree algorithm is used to automatically select the trajectory and landing area for a general aviation aircraft in the event of a pilot losing control, while in the study of Hashemi et al. (2020), deep learning techniques are investigated to predict aircraft trajectories. In the studies of Pang et al. (2021) and Zhang and Mahadevan (2020), Bayesian neural networks and Bayesian deep learning models are used for flight trajectory prediction.

One of the topics covered in AI studies in aviation is related to aircraft maintenance processes. These studies mostly focus on predicting failures or failures that have not yet occurred. For example, in the study of Weckman et al. (2006), a decision support system was designed for engine restoration, and in the study of Kong (2014), AI was used to monitor engine performance and health. In the study of Chen et al. (2016), a real-time fault detection algorithm was used to monitor rotating components in aircraft engines. In the studies of Dangut et al. (2021) and Wang et al. (2019), particle swarm optimization and machine learning were investigated for the early detection of rare failures in aircraft engine bearings, while in the study of Matuszczak et al. (2021), machine and deep learning methods were used together to determine the condition of turbofan engine components. Of course, the studies conducted are not only related to aircraft engines. For example, in the study of Brandoli et al. (2021), the use of AI for aircraft fuselage corrosion detection was investigated, and in the study of S. Li et al. (2023) used deep learning algorithms to detect damage to aircraft wings.

Another topic addressed in AI studies concerns the physical characteristics of airports and ground handling facilities. For example, in the study of Ceylan et al. (2008), neural networks were used to determine the performance and damage of airport paved areas. Similarly, in the study of Kaya et al. (2018), neural networks were used for more practical pavement calculations of airport runways. In the study of Ip et al. (2010), a multi-agent-based model was developed for the optimization of maintenance vehicles in ground handling equipment maintenance processes.

Another topic addressed in AI studies is the reduction of flight delays. In the study of Wang and Gao (2013), Bayesian networks were used to reduce the safety risks arising from flight delays. In the studies of Alla et al. (2021) and Qu et al. (2020), artificial neural networks were used to predict flight delays, while machine learning was used in the studies of Hatıpoğlu et al. (2022) and Mamdouh et al. (2023). In the study of Lui et al. (2022), the Bayesian approach was used to investigate the effect of weather conditions on arrival delays.

Among the topics examined in AI studies are studies on the optimization of airports. In the study of Weiszer et al. (2015), it is stated that using a genetic algorithm to optimize all processes at an airport makes operations more efficient. In the study of Zhang et al. (2019), a regression model based on three neural networks was created to investigate the propagation effect of flight delays at airports, and in the study of Felkel et al. (2021), airports using AI were examined to determine the arrival times of aircraft from gate to gate more accurately. In the study of Zhang et al. (2022), the machine learning method was used to prevent vehicle collisions in airport ground operations, and in the study of Chow et al. (2022), an evolutionary algorithm was used to assign gates to aircraft in airport terminal buildings. In the study of Mangortey et al. (2022), the machine learning method was used to analyze and evaluate airport operations, and Du et al. (2022) used a deep learning approach to estimate airport capacity accurately. Öztürk and Kuzucuoğlu (2016) mentioned the development of fully autonomous robots to collect objects that could cause foreign object damage (FOD) at airports. Adi et al. (2022) used convolutional neural networks to detect FODs to increase aviation safety.

Another topic addressed in AI studies is related to weather forecasting. In the study of Boneh et al. (2015), Bayesian networks were used for fog prediction activities at the airport, while in the studies of Bartok et al. (2022) and Shankar and Sahana (2023), a machine learning approach was adopted to predict visibility and fog. In the study of Herman and Schumacher (2016), a model using machine learning algorithms was designed for more accurate weather prediction around the airport, while in the study of Kaewunruen et al. (2021), the deep learning method was used for the same purpose. In the studies of Alves et al. (2023) and Kim and Lee (2021), the machine learning method was used for more accurate wind predictions. In the studies of Menegardo-Souza et al. (2022) and Muñoz-Esparza et al. (2020), a machine-learning model was used to detect turbulence during flight.

Machine learning and aircraft irregular motion algorithms were used to predict unusual weather conditions around airports by Jan and Chen (2019). Machine learning was used to detect icing areas to prevent aircraft icing Sim et al. (2018).

In AI studies, many individual studies cannot be evaluated under any group. For example, in the study of Li et al. (2017), an xor-based algorithm was developed to design a system that can take control of an aircraft in the event of a hijacking or pilots' suicidal intentions. In the study of Habler and Shabtai (2018), a long short-term memory decoder was designed to detect fake messages sent from the Automatic Dependent Surveillance-Broadcast (ADS-B) system by an attacker or a hijacked aircraft. In the study of Ko et al. (2017), heuristic algorithms were used for more efficient and effective fleet assignment and routing under carbon restrictions due to EU-ETS requirements. In the study by Singh (2018), it was stated that airline companies wanted to reduce fuel consumption due to environmental and economic concerns, and a real-coded genetic algorithm was developed to reduce fuel consumption. In the study of Baumann and Klingauf (2020), a machine-learning method was used to model aircraft fuel consumption. In another study, Zhu and Li (2021) used a deep learning method to reduce fuel consumption. In the study of Wu et al. (2022), metaheuristic algorithms were utilized for hub and spoke network design and fleet planning.

When the literature is reviewed, it is seen that studies have also been conducted on aircraft hard landings. For example, Tong et al. (2018a) developed a deep prediction model based on Long Short-Term Memory to predict aircraft hard landings. Similarly, AI was used to predict aircraft landing speed to increase flight safety, and a model based on long short-term memory was created. Tong et al. (2018b) and Puranik et al. (2020) used the supervised machine learning technique to predict aircraft critical landings, and Kong et al. (2022) used the Bayesian deep learning method for the safety assessment of hard landing problems.

AI studies have also been conducted on education topics in the aviation sector. For example, in the study of Siyaev and Jo (2021), a metaverse was created in aircraft maintenance training, and topics such as deep learning, convolutional neural networks, and machine learning were tested. Mnaoui et al. (2022) examined a machine learning method proposed for use in emergency communication training of air traffic controllers. Kabashkin et al. (2023) examined the use and teaching of AI in aviation engineering curricula. In the study of Albelo and McIntire (2023), how aviation education professionals can use and adapt AI applications in the classroom was discussed.

As can be seen, many studies on AI in aviation have been conducted. However, the literature is not limited to the ones mentioned here. With recent technological advances, the number of these studies is constantly increasing. In this context, it is thought that the studies on AI in the air transportation sector, which is one of the leading sectors in technology development, should be analyzed in depth. One of the methods that enable in-depth analysis of the literature is bibliometric analysis. Bibliometric analysis helps reveal a general perspective by evaluating all studies related to a field instead of analyzing the studies individually. On the other hand, bibliometric analysis helps to reveal the trends and effectiveness of studies in a field (Bızel, 2023). Bibliometric analyses significantly contribute to the evaluation of existing literature by enabling analyses such as performance analysis, citation and co-citation analysis, bibliographic matching, co-author analysis, and common word analysis (Karakavuz, 2023). Bibliometric analyses are more reliable because they have a strong mathematical basis, provide quantitatively accurate findings, and reduce subjectivity bias (Donthu et al., 2021). In this context, using bibliometric analysis in this study was deemed appropriate.

3. Materials and Methods

In this study, a bibliometric analysis of the studies on AI in the air transport sector published in journals indexed by Scopus between 2003 and 2023 has been conducted and the findings obtained have been quantified and visualized. Data collection and data analysis processes are explained in detail below.

3.1. Data Collection

The data within the scope of the study were obtained from the Scopus database, which is used extensively by researchers. Scopus database is preferred for bibliometric analysis in social sciences because it contains more scientific articles than Web of Science, can present a large number of data together, and is a comprehensive database (Falagas et al., 2008; Singh et al., 2021). The Scopus database was searched using the keywords 'artificial intelligence' and 'aviation' for articles published only in English and, final versions. Only articles published between 2003 and 2023 were included in the study. On the other hand, studies in Biochemistry, Genetics and Molecular Biology, Medicine, Agricultural and Biological Sciences, Nursing, Pharmacology, Toxicology and Pharmaceutics, Immunology and Microbiology, Dentistry, and Veterinary Medicine were excluded. As a result of these limitations, a total of 1824 studies were reached. 1824 articles were examined, 112 of which were not related to air transportation and were removed from the study data. In this context, 1712 articles were found to be related to air transportation. Bibliometric aspects were investigated by analyzing the number of citations, average number of citations per study, most cited studies, most productive authors and countries, collaborations between countries, most frequently used keywords, co-occurrence, co-citation, and bibliographic coupling. Figure 1 shows the design of the study. Finally, the study data consists only of articles published in Scopus between 2003 and 2023, which constitutes a limitation of this study.

3.2. Data Analysis

Bibliometric analysis is a type of analysis that considers bibliographic characteristics such as collaborations, keywords, authors, and countries to learn about social networks and structures in a field and to determine which themes emerge in studies conducted in the field (Zupic and Čater, 2015). Bibliometric analysis provides insights into the evolution of science by systematically analyzing literature (Pessin et al., 2022). To reveal bibliometric features in the study, performance analysis was performed using R bibliometrix software, followed by science mapping analysis using VOSviewer software.

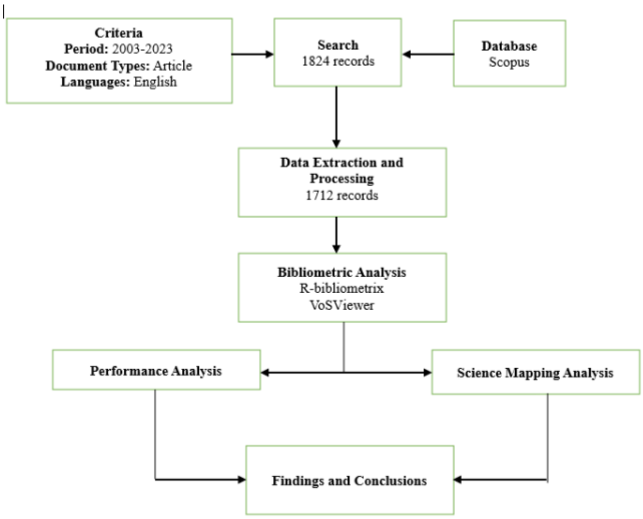

Figure 1. Bibliometric analysis flow chart.

3.2.1. Performance Analysis

Performance analysis is a type of bibliometric analysis in which quantitative data such as the amount and impact of production, authors, institutions and countries, number of citations, and the most cited publications can be obtained in a particular research area after the data are obtained (Moral-Muñoz et al., 2020). In performance analyses, authors present the quantitative information they deem necessary and valuable in their studies. In this study, the most productive authors and citation counts, most productive institutions, responsible author countries and international collaboration rates, country citation counts, word cloud analysis, and thematic analysis were carried out.

3.2.2. Science Mapping Analysis

Science mapping analysis aims to obtain an overview of scientific knowledge in a research area (Pessin et al., 2022). In other words, science mapping analysis is the graphical representation of how knowledge in a field is related in terms of countries, authors, and articles (Small, 1999). Network analysis is at the heart of scientific mapping analysis. Network analysis allows us to perform statistical analysis on the maps created to show different measurements of the whole network, measurements of relationships, or the overlap of different clusters (Aria and Cuccurullo, 2017). In this study, co-occurrence, co-citation, and bibliographic coupling analyses from scientific mapping analyses were performed.

4. Results

4.1. Results of Performance Analysis

In this study, bibliometric analysis of studies on AI applications in the air transportation sector published in journals scanned in the Scopus database was carried out. The data covers studies published between 2003 and 2023. Analyses were conducted on a total of 1712 articles. Table 1 shows the descriptive statistics of the published studies.

As seen in Table 1, 1712 articles were published in a total of 724 journals. While the annual growth rate of publications is 20.57%, the average age of documents is 5.12 years. While the authors used a total of 5259 keywords in their studies, the number of keyword plus determined by Scopus is 11097. Out of 1712 articles, only 94 articles have a single author. This shows that the rate of collaboration in AI studies is high. The author collaboration rate per document is 3.9. The international co-authorship rate is 22.84, indicating that the international collaboration rate is relatively low.

Table 1. Descriptive statistics for bibliometric data

Description	Results
Main Information About Data	
Timespan	2003:2023
Sources (Journals)	724
Documents	1712
Annual Growth Rate %	20.57
Document Average Age	5.12
Average Citations Per Doc	18.48
Document Contents	
Keywords Plus	11097
Author's Keywords	5259
Authors	4812
Authors of Single-Authored Docs	89
Authors Collaboration	
Single-Authored Docs	94
Co-Authors Per Doc	3.9
International Co-Authorships %	22.84

Figure 1 shows the historical development of scientific studies in literature. Accordingly, studies on AI in air transportation grew with a relatively small momentum between 2003 and 2017 but gained great momentum after 2017. The average number of citations per publication increased significantly in 2007, but this increase was not sustained in the following years.

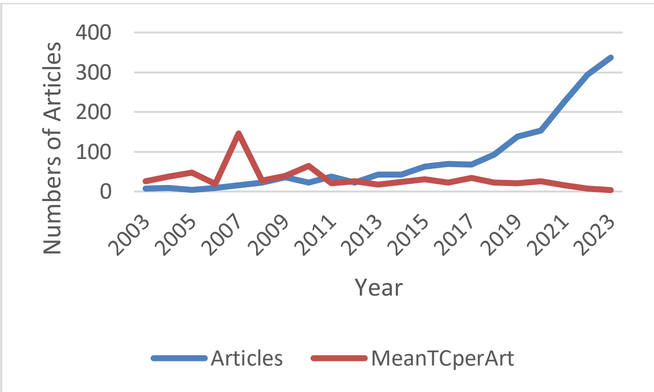

Figure 1. Number of publications and mean total citations by year

At the heart of progress in a scientific field are the authors of scientific production, who provide a better understanding of the boundaries of the scientific field Bakır et al. (2022). In this context, it is important to identify the most productive authors within the scope of performance analysis. The results of the analysis of the top 10 most productive authors are shown in Table 2.

As seen in Table 2, Zhang X is the most productive author in terms of the number of publications (A:31), number of citations (TC:726), and number of citations per article (TC/A:23,41). In terms of h-index, the most productive author is Zhang J with 13 publications receiving at least 13 citations. Considering the countries of the authors with the highest number of publications on AI in the air transportation sector, there are only 13 authors from outside Asian countries in the top 100. Of the 887 publications in the top 100, 800 were made by Asian authors. Therefore, it can be said that the Asian region is of great importance in the development of studies on AI in the air transportation sector. Lotka's Law analysis describes scientific productivity and the relationship between authors and the number of their articles by estimating an author's contribution to a publication (Kushairi and Ahmi, 2021). When the author productivity is analyzed with Lotka's law analysis, there are 3985 authors contributing to only 1 document, 464 authors contributing to 2 documents, 185 authors contributing to 3 documents, 72 authors contributing to 4 documents, 32 authors contributing to 5 documents, 21 authors contributing to 6 documents, 18 authors contributing to 7 documents, 3 authors contributing to 8 documents, 7 authors contributing to 9 documents, and 3 authors contributing to 10 documents. In other words, it can be said that most of the authors are involved in only one document.

Table 2. Most productive authors

Authors	A	TC	TC/A	h-index
Zhang X	31	726	23,41	12
Zhang J	30	626	20,86	13
Liu Y	27	410	15,18	10
Li J	25	295	11,8	9
Wang J	25	273	10,92	8
Li Y	23	290	12,6	9
Zhang Y	23	241	10,47	11
Wang Y	22	473	21,5	8
Chen H	20	224	11,2	8
Li X	20	182	9,1	6

TC: Total Citations, A: Articles
The ranking was made based on the number of publications.

Another analysis conducted within the scope of performance analyses is related to the organizations that most support AI efforts in air transport. Table 3 shows the top 10 organizations that support AI in air transport the most. As seen in Table 3, the organizations that support AI in air transportation the most are the organizations in China. While 302 of the 376 studies in the top 10 are supported by Chinese organizations, 27 are supported by British and 47 by American organizations.

Table 3. Most productive institutions

Institutions	Articles
Beihang University (China)	73
Nanjing University of Aeronautics and Astronautics (China)	73
Civil Aviation University Of China (China)	53
Civil Aviation Flight University Of China (China)	32
Cranfield University (UK)	27
Northwestern Polytechnical University (China)	25
Purdue University (USA)	24
Shanghai Jiao Tong University (China)	23
Sichuan University (China)	23
University of California (USA)	23

Another issue examined within the scope of performance analysis is international cooperation. The results of the analysis conducted in the context of the responsible author's countries are shown in Table 4. As seen in Table 4, although China is the country with the highest number of publications (A:428) and a quarter of all publications, the country with the highest international cooperation is France (MCP%: 38.9). The second country with the highest international collaboration rate is Australia with 38.1%. However, France and Australia represent only 4.6% of all publications.

Table 4. Corresponding author countries and international collaborations

Country	A	SCP	MCP	Freq	MCP %
China	428	348	80	0,25	0,187
USA	222	191	31	0,13	0,14
UK	67	45	22	0,039	0,328
Germany	65	47	18	0,038	0,277
India	60	47	13	0,035	0,217
Australia	42	26	16	0,025	0,381
Italy	42	29	13	0,025	0,31
Korea	38	27	11	0,022	0,289
France	36	22	14	0,021	0,389
Canada	35	23	12	0,02	0,343

SCP: Single Country Production, MCP: Multi-Country Production, A: Articles.

Another issue addressed within the scope of performance analysis is the total number of citations received by countries. Table 5 shows the total number of citations received by the top 10 countries.

Table 5. Country citation numbers

Country	TC	AAC
USA	6634	29,90
China	4857	11,30
Germany	2418	37,20
India	1505	25,10
Italy	1359	32,40
Canada	1246	35,60
UK	963	14,40
France	842	23,40
Australia	718	17,10
S. Korea	711	18,70

AAC: Average Article Citations, TC: Total Citations

As seen in Table 5, the country with the highest number of citations (TC: 6634) is the USA, followed by China (TC: 4857). In terms of the number of publications, China (A:428) has the highest number of publications, but in terms of the number of citations, America has received more citations than Chinese publications. On the other hand, Germany (AAC: 37.2) has the highest average article citation rate. Canada (AAC: 35.6) ranks second in terms of average article citations. This may be because researchers from Germany and Canada focus on current issues, study more general topics, conduct review studies, or conduct more qualified studies. Although China ranks first in terms of the number of publications and second in terms of total citations, the reason why China ranks last among the top 10 countries in terms of average article citations may be an indication that Chinese researchers tend to focus on very specific fields.

Another analysis performed within the scope of performance analysis is the word cloud analysis created from keywords. Figure 2 shows the word cloud created from the authors' keywords. While creating the word cloud, the keywords 'aviation', 'air transportation', 'civil aviation' and 'article' were not included in the analysis, considering that these keywords would be found in every study. As seen in Figure 2, the most used keywords in studies on AI in air transportation are air traffic control, aircraft, decision making, deep learning, machine learning, artificial intelligence, aircraft accidents, risk assessment, airports, and air navigation.

Figure 2. Wordcloud

Thematic analysis was the last analysis conducted within the scope of performance analysis. Thematic analysis is one of the most powerful analyses used to show the development of a scientific field (Bakır et al., 2022). The thematic analysis creates clusters based on recurring keywords and thus provides a more objective insight (Bajaj et al., 2022). Figure 3 shows the thematic map created using the Louven algorithm.

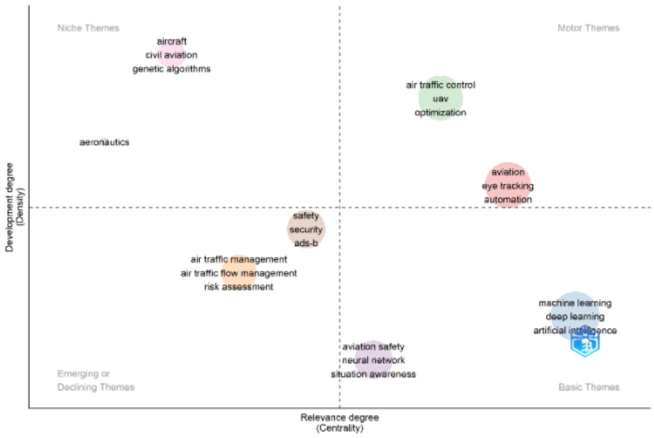

Figure 3. Thematic map

As seen in Figure 3, the motor themes (quadrant II) in AI studies in air transport are air traffic control, UAV, optimization, eye tracking, and automation. Basic themes (quadrant IV) are machine learning, deep learning, aviation safety, neural networks, and situation awareness. Emerging or declining themes (quadrant III) are safety, security, ads-b, air traffic management, air traffic flow management, and risk assessment. Finally, aircraft, genetic algorithms, and aeronautics emerged as niche themes (quadrant I). In this context, it can be said that genetic algorithms and aeronautics are more narrowly studied, while air traffic management, air traffic flow management, risk assessment, and ads-b are on the rise. On the other hand, it can be stated that machine learning, deep learning, neural networks, and situational awareness continue to be studied in AI studies from the past to the present. Finally, it can be mentioned that air traffic control, UAV and optimization, eye tracking, and automation are currently the most studied topics, and eye tracking and automation are on their way to becoming one of the main topics of the field.

4.2. Results of Science Mapping Analysis

Scientific mapping analyses are widely used in bibliometric studies (Karakavuz, 2023). In this study, co-occurrence analysis, co-citation analysis, and bibliographic coupling analysis were performed within the scope of scientific mapping analysis.

The first analysis performed within the scope of scientific mapping analyses in the study is co-occurrence analysis. Co-occurrence analysis is one of the important analyses for making inferences about scientific knowledge structures and trends in the research field Wang et al. (2020). This analysis helps to understand how researchers evolve and change in response to changes in concepts, issues, and societal trends Hassan and Duarte (2024). Figure 4 shows the co-occurrence analysis network realized within the scope of the study.

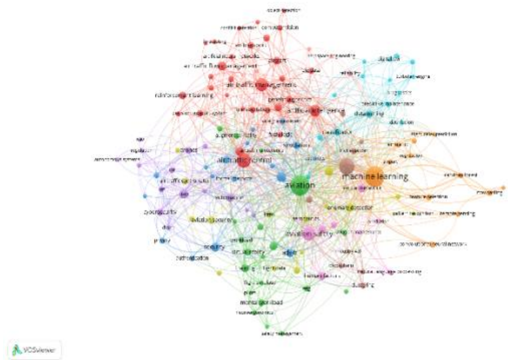

Figure 4. Co-occurrence analysis

As seen in Figure 4, ten different clusters emerged because of the co-occurrence analysis. The red cluster is the largest cluster with 30 items. In this cluster, the keywords air traffic management and air traffic control are the nodes, and topics such as prediction, conflict detection, optimization, and genetic algorithms were studied within the scope of air traffic topics. The keyword that coexists the most in this cluster is air traffic control with 53 occurrences, 36 links, and 57 total link strength. The green cluster constitutes the second largest group with 20 items. The node of this cluster is aviation, and studies were carried out on topics such as pilots, situational awareness, training, eye tracking, and attention. The most co-occurring keyword in this cluster is aviation with 100 co-occurrences, 70 links, and 137 total link strength. The third largest cluster is the blue cluster with a total of 17 items. The nodes of this cluster are risk assessment, safety, and security. This cluster focuses on safety and security issues in air-ground communication by studying topics such as identification, privacy, risk assessment, and ads-b. The keyword with the highest co-occurrence in this cluster is safety with 24 co-occurrences, 35 links, and 44 total link strength. The fourth largest cluster is the yellow cluster with a total of 15 items. The nodes of this cluster are deep learning and anomaly detection. In this cluster, topics such as collision avoidance and unmanned aerial vehicles are studied based on aviation safety and security issues. The most effective keyword of this cluster is neural networks with 20 co-occurrences, 22 links, and 29 total link strength. The fifth cluster again contains 15 items and is shown in purple. This cluster focuses on automation and regulation of drones, UAVs, and Unmanned Aircraft Systems (UAS). The most influential keyword in this cluster is UAV with 20 co-occurrences, 20 links, and a total link strength of 28. The sixth cluster again contains 15 items and is shown in light blue. The studies in this cluster mostly consist of studies on predicting the failures that may occur in aircraft maintenance. The most effective keyword of this cluster is data mining with 16 co-occurrences, 15 links, and a total link strength of 20. The seventh cluster consists of 12 items and is shown in orange. The node of this cluster is machine learning. This cluster includes studies that try to predict delays and turbulence in air traffic and airports. The most influential keyword of this cluster is machine learning with 100 co-occurrences, 59 links, and 143 total link strength. The eighth cluster consists of 9 items and is shown in brown. This cluster includes studies focused on topics such as deep learning and LTSM methods, blockchain, and aircraft maintenance. The most influential keyword of this cluster is deep learning with 67 co-occurrences, 46 links, and 81 total link strength. The ninth cluster has 8 items and is shown in pink color. The node of this cluster is aviation safety. In this cluster, there are mostly studies investigating human factors in ensuring aviation safety. The most influential keyword of this cluster is aviation safety with 48 co-occurrences, 39 links, and 61 total link strength. The tenth cluster has 4 items and is shown in light red. Studies in this cluster focus on topics such as space engineering, reliability, and uncertainty. Table 6 shows the keywords included in the Co-occurence analysis.

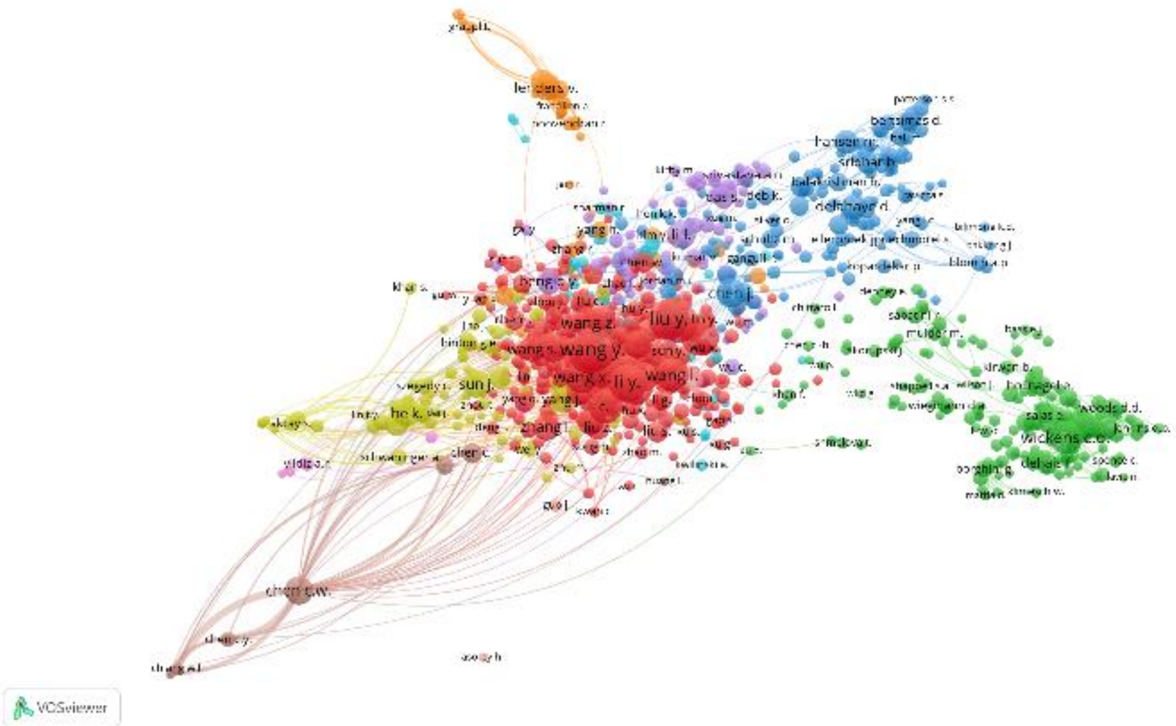

Figure 5. Co-citation analysis

As seen in Figure 5, 10 clusters emerged as a result of co-citation analysis. The first cluster is colored red, and the nodes of the cluster include authors such as Wang Y, Liu Y, Zhang H, Wang I, and Wang X. There are a total of 350 authors in this cluster. The most influential author of this cluster is Wang Y with 444 citations, 895 links, and 24196 total link strength. The second cluster is shown in green and there are 173 authors in this cluster. The nodes of this cluster include authors such as Wickens, C.D., Stanton N.A., Endsley M.R., Wiegman D.A., and Hollnagel E. The most influential author of this cluster is Wickens C. D. with 253 citations, 573 links, and 9344 total link strength. The third cluster is shown in blue color and there are 158 authors in this cluster. Authors such as Hansen M., Hansman R.J., Delahaye D., and Hwang I. are located at the nodes of this cluster. The most influential author of this cluster is Delahaye D. with 145 citations, 627 links, and 6154 total link strength. The fourth cluster is shown in yellow color and there are 100 authors in this cluster. The nodes of this cluster include authors such as Sun J., Yang J., Girshick R., He K., and Liu W. The most influential author of this cluster is Sun J. with 182 citations, 788 links, and 13049 total link strength. The fifth cluster is colored purple and contains 76 authors. The nodes of this cluster include authors such as Mahadevan S., Schmidhuber J., Hington G., Li L., Das, S., Srivastaya A.N., and Bengio Y. The most influential author in this cluster is Li L. with 188 citations, 777 links, and 8672 total link strength. The sixth cluster is shown in light blue and there are 40 authors in this cluster. The nodes of this cluster include authors such as Lee S., Kim S., Lee D., Chen F., Breiman I., and Chan P.W. The most influential author of this cluster is Breiman I. with 72 citations, 526 links, and 2321 total link strength. The seventh cluster is shown in orange and there are 33 authors in this cluster. The nodes of this cluster include authors such as Strohmeier M., Lenders V., Schafer M., and Maurer N. The most influential author of this cluster is Lenders V. with 155 citations, 410 links, and 6949 total link strength. The eighth cluster is shown in brown and there are 8 authors in this cluster. The nodes of this cluster include authors such as Chen C.W., Chen C.Y., Chen T., and Chen C. The most influential author of this cluster is Chen C. W. with 194 citations, 171 links, and 22261 total link strength. The ninth cluster is shown in pink color and there are 5 authors in this cluster. Kumar S. and Yıldız A.R. are located at the node of the cluster. The tenth and last cluster is colored in light red and there are 3 authors in this cluster.

Table 6. Co-occurrence keywords

Cluster 1 (Red)	Cluster 2 (Green)	Cluster 3 (Blue)	Cluster 4 (Yellow)	Cluster 5 (Purple)	Cluster 6 (Light blue)	Cluster 7 (Orange)	Cluster 8 (Brown)	Cluster 9 (Pink)	Cluster 10 (Light red)
Air traffic control	Aircraft maintenance	Ads-b	Aeronautics	AI	Artificial neural network	Air traffic	Aviation industry	Aviation maintenance	Aerospace engineering
Air traffic flow management	Attention	Authentication	Air traffic control (ATC)	Automation	Classification	Airport	Blockchain	Aviation safety	Mixed reality
Air traffic management	Augmented reality	Bayesian network	Anomaly detection	Autonomous systems	Data fusion	Convolutional neural network	Civil aviation	Human error	reliability
Air transport	Aviation	Formal methods	Aviation security	Communication	Data mining	Feature selection	Clustering	Human factors	Uncertainty
Air transportation	Education	Internet of things	Collision avoidance	Covid-19	Decision making	Flight delay prediction	Deep learning	Natural language processing	
Aircraft	EEG	Modeling	Flight data	Cybersecurity	Digital twin	Machine learning	Industry 4.0	Neural network	
Airport operations	Eye tracking	Petri nets	Flight safety	Decision-making	Fault diagnosis	Nowcasting	Long short-term memory	Prediction	
Artificial intelligence	Fatigue	Privacy	LTSM	Drone	Ontology	Random forest	Maintenance	Situation awareness	
Artificial intelligence	Flight Simulation	Risk assessment	Neural networks	Drones	Predictive maintenance	Regression	Text mining		
Artificial neural networks	Mental workload	Safety	Path planning	ICAO	Prognostics	Remote sensing			
Big data	Neuroergonomics	Safety assessment	Pattern recognition	IoT	Prognostics and health management	xgboost			
Computer vision	Pilot	Security	Performance evaluation	Regulation	Remaining useful life	Turbulence			
Conflict detection	Pilots	Simulation	Risk	Technology	Structural health monitoring				
Conflict detection and resolute	Principal component analysis	System Safety	Time series	UAS	Turbofan engine				
Decision support system	Safety management	Unmanned aerial vehicle	Unmanned aerial vehicle (UAV)	UAV	Vibration				
Decision support systems	Situational awareness	Unmanned aircraft							
Forecasting	Support vector machine	Unmanned aircraft systems							
Fuzzy logic	Training								
Genetic algorithm	Virtual reality								
Genetic algorithms	Workload								
Multi-criteria decision									
Multi-objective optimization									
Object detection									
Optimization									
Particle swarm optimization									
Reinforcement learning									
Sustainability									
Sustainable aviation									
Trajectory prediction									
Transportation									

The last analysis performed within the scope of science mapping analysis is bibliographic coupling analysis. Bibliographic coupling analysis is essentially a technique for finding conceptual similarities when citing a document (Pandey et al., 2023). In other words, if an article is included in the bibliography of two or more articles, it can be said that these articles are bibliographically merged Haghani et al. (2021). In this study, bibliographic coupling analysis was conducted based on journals. In this way, it is aimed to reveal which journals are related to each other in the field of air transportation. Figure 6 shows the bibliographic coupling analysis network.

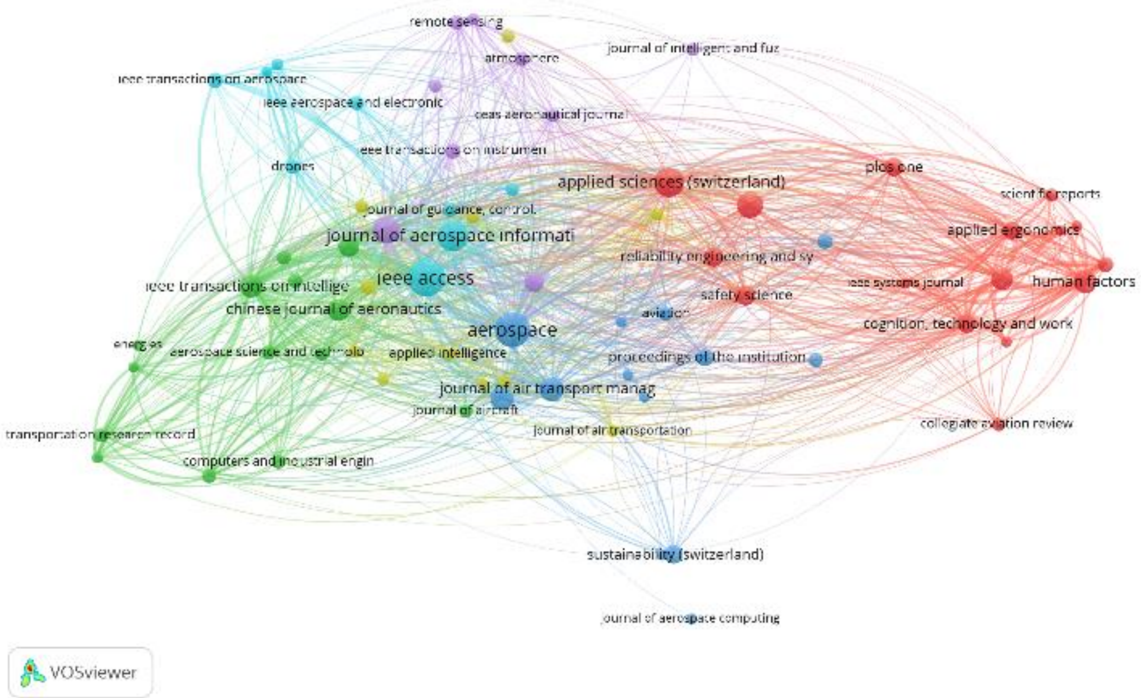

Figure 6. Bibliographic coupling analysis

As seen in Figure 6, six different clusters emerged because of bibliographic coupling analysis. The first cluster is shown in red color, and it can be mentioned that more journals in this cluster cover human factors and ergonomics topics related to AI. The most influential journal in this cluster is Applied Science (Switzerland), with 34 articles, 60 citations, and 580 total link strength. The second cluster is shown in green and it can be seen that there are more journals directly related to air transport in this cluster. The most influential journal in this cluster is IEEE Transaction on Intelligent Transportation Systems with 22 articles, 60 citations, and 881 total link strength. The third cluster is shown in blue, and it is seen that the journals in this cluster are mostly composed of journals that publish policy-oriented publications in the air transport sector. The most influential journal in this cluster is Aerospace with 50 articles, 68 citations, and 987 total link strength. The fourth cluster is shown in yellow color, and it is seen that the journals in this cluster mostly publish on engineering science. The most influential journal in this cluster is Engineering Applications of Artificial Intelligence with 9 articles, 41 citations, and 114 total link strength. The fifth cluster is shown in purple, and it is seen that the journals in this cluster publish on meteorology, applied sciences, and air transportation systems. The most influential journal in this cluster is Transportation Research Part C with 31 publications, 59 citations, and 1076 total link strength. The sixth and last cluster is shown in light blue, and it is seen that the journals in this cluster mostly publish on space sciences. The most influential journal in this cluster is IEEE Access with 54 articles, 67 citations, and 892 total link strength. On the other hand, it should also be mentioned that all clusters are interrelated. The air transportation system carries out its operations interconnected like a chain. Therefore, scientific progress or application in any field will have an impact on the entire system. Accordingly, it is quite normal for the clusters to have a strong relationship with each other.

5. Discussion and Conclusion

A review of the literature reveals that there has been a noticeable increase in studies on AI in the last five years. A similar situation can be mentioned in the studies in the air transportation sector. This situation requires knowing how, by whom, in which direction, and on which topics literature has developed. For this purpose, it is aimed to conduct a retrospective analysis of the studies on AI in the air transportation sector between 2003-2023 using the bibliometric analysis method. To achieve this goal, 1712 articles were obtained from the Scopus database, and analyses were performed on these articles. Performance analyses were performed using R biblometrix, and scientific mapping analyses were performed using VOSviewer software.

The results of the analysis show that a total of 4812 authors contributed to AI studies in air transportation in 1712 articles, 94 articles were single-authored, there was an average of 3.9 authors per document, and the international collaboration rate in these studies was 22.84%. When the studies are evaluated in terms of international cooperation, it can be said that only a quarter of them are international and the cooperation rate is relatively low. This can be considered as an indicator that the culture of cooperation in AI studies in the air transportation sector has not developed much. On the other hand, France (38.9%) and Australia (38.1%) have the highest rate of international collaboration. However, the share of these two countries in all publications is 4.6%. It is thought that the inclusion of more international collaborations in AI studies in an inherently international sector such as air transportation will contribute to increasing the benefits to be obtained. It is stated in the literature that increased collaborations increase the impact of the publication and the likelihood of citation (Glänzel et al., 1999) and facilitate joint learning (Laal et al., 2013).

As a result of the analysis, it was revealed that the studies on AI in the air transportation sector have accelerated after 2017. Of the 1712 articles in the analyzed sample, 1321

(77.16%) were published in 2017 and later. The result that the number of studies on AI has increased very rapidly after 2017 has also emerged in some studies (Yang et al., 2024). Innovations and developments in the field of computers and technology can be considered as the main reason for this. On the other hand, the use of AI applications in areas such as business, economy, agriculture, social development, medical sciences, unmanned driving, intelligent assistants, human resources, purchase intention prediction, and IoT also causes the number of academic studies to increase (Yang et al., 2024).

As a result of the analysis, it is seen that Zhang X. (A: 31, TC: 726) is the author who contributed the most to the field. Zhang J. (A: 30, TC: 626) ranked second and Liu Y. (A: 27, TC: 410) ranked third. On the other hand, when the countries that contributed the most to the field were examined, it was found that 25% of all publications were produced by China, the second place was the USA (13%) and the third place was the UK (3%) (see Table 2 and 3). On the other hand, when the institutions that support AI studies are examined, it is seen that 7 of the top 10 institutions are Chinese institutions (see Table 3). As can be seen, Chinese publications dominate the field both in terms of countries and authors. In many studies, it is mentioned that China is on its way to becoming a technology and science superpower (Wang and Feng, 2024). Some of China's policies in the last quarter century have led to an increase in the number and quality of academic publications. Some of these policies include the requirement for Chinese researchers to publish in the Science Citation Index or Social Science Citation Index to obtain a PhD degree, the possibility for researchers who have gone to developed countries to return to their home countries and work in both academic and practitioner positions, the sharing of knowledge with the people they work with, and the Chinese government's allocation of more resources to research and development activities (Karakavuz, 2023). With these policies, the pressure on Chinese researchers is increased and hence there is a noticeable increase in the number of academic publications.

As a result of the analysis, it was revealed that the topics that have been studied in the field for a long time and can be described as basic themes are machine learning, deep learning, neural networks, and situational awareness. In other words, it would not be wrong to say that the first academic studies on AI in aviation were carried out to increase or detect the situational awareness of aviation employees, and to say that machine learning, artificial neural networks, and deep learning methods are used to achieve this purpose. The current most studied topics (motor themes) are air traffic control, UAV, eye tracking, and automation. With the progress of the area, it is seen that AI studies in aviation are shifting to issues such as air traffic systems, UAVs and automation. One of the most popular issues of today is undoubtedly UAVs. UAVs are used in cargo transportation, military aviation, passenger transportation, agricultural practices and many other areas. Therefore, it is very common for the academic community to carry out studies for the development of this area. Air traffic control is an element that becomes even more apparent as the traffic volume in the airports increases. Therefore, the use of AI applications to solve the problems and difficulties within the air traffic system has been quite increasing in recent years. This is of course reflected in academic publications. One of the most studied issues in recent years is automation. In today's world, almost everything is autonomous to the electronic devices we have used in our homes. To reduce the impact of the human factor in aviation, aircraft, drones, air traffic control systems and other used equipment are tried to be autonomous in parallel with the developments in the AI field. As a matter of fact, this situation also manifests itself in academic studies. The emerging themes are safety, security, ads-b, air traffic management, air traffic flow management, and risk assessment. It can be mentioned that the use of AI has become popular to ensure the safety and security of air traffic management, to prevent data leaks and to carry out risk assessments more accurately. Finally, the niche themes are genetic algorithms and airplanes (see Fig 3). In the studies related to AI, a narrow researcher has established a connection between aircraft and genetic algorithms. This connection is thought to be established for purposes such as increasing the efficiency of the airplanes, developing safety and security issues and making aircraft autonomous.

The co-occurrence analysis, one of the science mapping analyses conducted for AI studies in air transportation, revealed 10 different clusters (see Fig 4). The largest cluster is shown in red color and this cluster, the keywords air traffic management, air traffic control, forecasting, and conflict were studied together. At the center of this cluster is the keyword air traffic control. This cluster includes studies carried out to reduce conflicts between aircraft (requesting priority, not losing the take-off-landing order, etc.) that occur during air traffic service. The second largest cluster is colored green, and in this cluster, the keywords aviation, pilots, situational awareness, and training worked together. The keyword aviation is at the center of this cluster. When the keywords in this cluster are examined, it is understood that the use of AI applications is being investigated in the training to be given to improve the situational awareness of pilots. The third largest cluster is shown in blue and the topics that worked together the most in this cluster are identification, risk assessment, safety, and ads-b. At the center of the cluster is the keyword safety. Studies on the necessity of correctly identifying risk factors to increase safety in this cluster have been examined in the context of AI.

Another science mapping analysis is co-citation analysis. In this study, co-citation analysis was performed on an author-based basis (see Fig 5). The analysis revealed 10 different clusters. The first cluster is shown in red, with Wang, Y. at the center of the cluster. The second cluster is colored green, with Wickens, C. D. at the center of the cluster. The third cluster is colored blue, with Delahaye, D. at the center of the cluster. When the co-citation analysis results are evaluated, it is seen that the authors give more citations to the authors in their geography in terms of co-citation. As stated in the study of Thelwall and Maflahi (2014), the authors read the publications from their own countries more and tend to ignore the articles from some other countries. On the other hand, in the study of Moed (2005), it is stated that the US authors give partially more citations to the articles in their own countries. Therefore, it is thought that the results in the co-citation analysis may be due to this situation. The last science mapping analysis performed was the bibliographic coupling analysis (see Fig 6). The analysis was performed based on journals. As a result of the bibliographic coupling analysis, 6 different clusters emerged. The first cluster is shown in red, and the Applied Science (Switzerland) journal is at the center of the cluster. The second cluster is colored green, and the center of this cluster is IEEE Transaction on Intelligent Transportation Systems. The third cluster is colored blue, and the center of this cluster is the journal Aerospace.

This study aims to provide an overview of the historical development of studies on AI for air transportation system and to define the structure of the research field. The main contribution of this study is to reveal the general structure of the research field and to serve as a guide for researchers who want to get acquainted with the existing literature. Through the study, researchers will be able to obtain statistical information such as the most productive authors, countries, and most cited studies in the field, and to identify gaps by monitoring the development direction of the literature.

In today's world, AI applications are no longer confined to the lab or a niche field of study but are now pervasive in every aspect of our lives. From creating communications, summarizing documents, and generating literature, to code engineering, translating languages, and synthesizing videos, AI work is emerging in every field, and the magnitude of its potential impact has caught even the most forward-thinking AI experts and technology visionaries off guard (Sellen and Horvitz, 2024). Therefore, raising awareness by comprehensively addressing past studies and existing literature will contribute to compensating for this unpreparedness, albeit to some extent. In this context, this study is expected to contribute to the understanding of existing literature to some extent. Finally, this study considers the air transportation system. In the future, separate studies on the components of the air transportation system such as airlines, airports, ground handling services, aircraft maintenance, aviation production, and air traffic control will contribute to a much clearer understanding of the effects of AI applications on the components of the sector.

Ethical approval

Not applicable.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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The Role of Flight Simulators in Pilot Training

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Abstract

Aviation is one of the most advanced and multifaceted industries in the world. One of the most critical aspects of aviation, which cannot be overlooked, is flight safety. Pilot training is a specialized form of education that is a crucial component of the aviation industry. The training process serves as a fundamental interface between pilots and the potential environments they will encounter in real flight operations. At present, a significant portion of pilot training is performed in flight simulators, which replicate real flight environments, making pilot training both cost-effective and safe. For example, a full flight simulator can provide accurate force feedback through its system for the flight control inputs of the pilot. Equipped with diverse systems to simulate various flight parameters (e.g. altitude, acceleration, speed, etc.), a flight simulator can generate a large amount of data on flight and pilot activity during training. With the continuous development of software and hardware technologies, flight simulators are becoming increasingly sophisticated, offering training across a broad range of tasks. Therefore, finding ways to enhance the efficiency and quality of simulator-based training is crucial. This study conducted a comparative analysis of the utilization of flight simulators both globally and within our country. The review of studies stresses the critical significance of pilot training in the aviation industry and the advantages that flight simulators bring to the training process. Furthermore, the need for objective evaluation of pilot performance is identified as a key issue that warrants global research attention.

1. Introduction

Positive developments in the field of aviation nowadays help improve air traffic. The demand for improving the practical and theoretical skills of the crew, including pilots, increases every day with the application of new technologies in aviation. Errors caused by human factors occur when the pilot has inadequate skills or gives unexpected reactions in an adverse situation. Although the consequences vary, the human factor plays a role in about 70 to 85 percent of aircraft accidents (Maurino et al., 2017). The majority of pilot-related errors, accounting for 80 percent of human factor-induced mistakes, are associated with deficiencies in pilot skills. Notably, approximately half of these errors serve as the initial trigger in the sequence of events culminating in flight accidents. (EASA, 2024). A primary approach to mitigating errors attributable to human factors involves improving pilot training, addressing unexpected in-flight situations through simulation, and continuously enhancing the overall training process (Socha et al., 2016).

Due to recent technological advancements, flight stimulators have become close enough to reality to eliminate concerns and doubts that may arise among pilots, aircraft manufacturers, airlines, or regulatory bodies. This has led to the significant spread of flight stimulators and their use as tools in the training and examination of military and civil flight crew qualifications. In response to the aforesaid developments, international standards and regulations have defined and detailed the requirements for the operational usage of flight simulators (EASA, 2018). Hence certified flight simulators are utilized in training, implementation of flight procedures, and pilot testing on a routine basis (Socha et al., 2016).

Including flight simulators in pilot training has provided some advantages, such as reducing risks arising from human factors, increasing training quality, increasing general flight training, and reducing training and aircraft operational costs (Aragon & Hearst, 2005). Furthermore, flight stimulators increase training effectiveness due to the possibility of adjusting the training course according to the skills of pilots or the outcomes of completed flights. Additionally, possible non-standard situations (caused by weather conditions or the aircraft's technical condition) can be created, and ways to cope with these situations can be worked on. Flight records can be accessed instantly, and accurate feedback is provided to pilots, which contributes to their progress (Haslbeck et al., 2014; Taylor et al., 2007).

In contemporary aviation, flight simulators are essential for pilot training and the reinforcement of critical skills. Simulation technologies have gained significance not only for educational purposes in both commercial and private aviation but also for investigating aircraft accidents, evaluating aircraft designs, and gaining deeper insights into ergonomic interactions. (Boril et al., 2015).

Advancements in avionics have significantly increased the complexity of both civil and military aircraft, leading to a heightened demand for crew training and a stronger reliance on flight simulators. Flight simulators have not only completely changed flight training methods with regard to decreasing risks and improving training quality; they have also considerably increased flight safety, reduced traffic density, and affected the environment positively. All of these have been ensured by reducing the costs of flight training. It is expected that the above-mentioned trends will continue in the foreseeable future (Allerton, 2010; Foyle and Hooe, 2010).

Pilots' manual flight experience decreases with the development of automation systems, which can lead to the loss of skills. Accidents, such as Air France 447 and Asiana Airlines 214 flights, are examples of accidents revealing the potential consequences of a lack of manual flight skills (Final Report, 2014; NTSB, 2012).

The present study investigated the potential of using flight stimulators and especially their contributions to basic flight skills and needs through a detailed literature review. The study examined the impacts of the transition from stimulated to real flights on the progress/regression in the maneuvers conducted. It also examined the applicability of mathematical methods in evaluating pilot training experience. The current work comprehensively reviewed research in the field of flight simulators and aimed to stress the contributions of different research topics from a general perspective, considering that simulators represent a complex human-machine system. Furthermore, it addressed the application areas of these training devices and discussed the terminology used in the literature.

2. Literature Review

The demand for new pilots increases every day with the growth of the aviation industry on a global scale. For instance, Boeing estimates that commercial aviation will need 674,000 new pilots worldwide in the following 20 years (Boeing, 2024). As of February 2023, aviation markets have fully recovered from the pandemic shock. It is expected that long-haul markets will recover to a considerable extent by the end of 2024. Overall, airlines have lost approximately four years of passenger growth because of the pandemic. It is expected that travel numbers will exceed 2019 levels in 2024 and reach an average annual growth rate of 3.8% by 2043 (IATA, 2024).

The most important question is not whether a pilot shortage will reoccur but when it will occur and how large the gap between supply and demand will be. A shortage of 34,000 pilots is predicted by 2025, with the most possible scenarios. In the most extreme scenarios, this shortage reaches 50,000. Ultimately, the impact of dismissals, retirements, and departures from the industry will create significant challenges for even the largest airlines. Airlines have a buffer of 100,000 pilots who are still receiving salaries but working reduced hours or are on voluntary company leave (Oliver Wyman, 2021).

According to the results of a survey conducted by Oliver Wyman in 2019 (Oliver Wyman, 2021), 62% of flight operations leaders indicated a shortage of qualified pilots as a major risk. The main reason for this impending pilot shortage varies by region. In the US, mandatory retirements due to an aging workforce, a decreased number of pilots leaving the military, and barriers to entry, such as training costs, are among the reasons for this shortage. In China and some other regions, capacity should be rapidly increased to meet the increasing demand for air travel with the rapid growth of the middle class. This impact also varies by airline class; 83% of regional carriers experience difficulties finding skilled personnel, while only 22% of low-cost carriers experience the same difficulties. Despite these differences, very few regions are not struggling to provide enough pilots to support future growth.

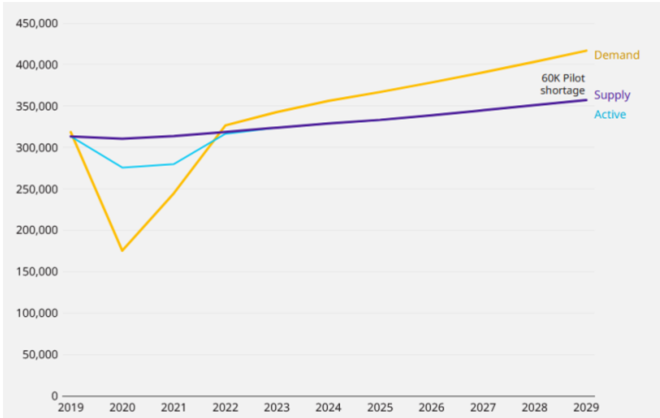

Figure 1. Global pilot demand versus supply (Oliver Wyman, 2021)

Student pilots have very little or no flight experience when they start their training (McLean et al., 2016). Training programs usually involve theoretical (ground school) and practical components (flight training). Ground courses include topics directly related to flight, such as aerodynamics, meteorology, navigation, and aircraft systems. This training is completed with a theoretical exam that students must pass before proceeding to more advanced practical courses (Marques et al., 2023).

Pilot training typically relies on a combination of various training aids and learning methodologies, structured around three key learning concepts: (1) theoretical studies, (2) training using Flight Simulation Training Devices (FSTDs), and (3) live training. The goal of flight simulation is to reproduce an aircraft's behavior as experienced by cockpit crew members during flight (on the ground) so that pilots can develop and maintain the skills required to operate the real aircraft safely and efficiently by flying the simulator and demonstrate their competence to the examiner (Baarspul, 1990).

Although the COVID-19 pandemic has created a temporary surplus of pilots, the time and costs associated with training, industry expansion, early retirement, and pilots transferring to other careers will continue to make a contribution to the pilot shortage in the foreseeable future. Considering the predicted increase in demand for new pilots, there is a need for faster and less expensive flight training programs to meet the demand better (Schaffernak et al., 2020).

In this regard, it is essential to review the literature to advance knowledge about the position of flight simulators in pilot training. Although numerous studies have been published on the subject, the literature has spread to various thematic areas, and studies have been published in various journals and conference proceedings. Characterizing the information in the literature and identifying opportunities for future research are some of the study's main objectives.

Socha et al. (2016) examined the effects of flight stimulator training before real flights on performance accuracy. The study was conducted on 35 student pilots who received private pilot training. The participants logged a total of 11 hours in a flight simulator, one hour in a Diamond DA40 aircraft, followed by an additional three hours in the simulator and two hours in real traffic. The maneuvers performed included 180° climbing and descending turns with a 30° pitch, maintaining a vertical speed of 500 ft/min. During the flight sessions, the instructor documented any deviations from the desired flight parameters. Socha et al. (2016) emphasized that the usage of flight simulators was partially reasonable but that five flight hours (for PPL - Private Pilot Licence) were inadequate to master basic flight skills.

Numerous studies have been carried out on modeling human behavior, including that of pilots. The majority of these studies are based on a definition initially proposed by D.T. McRuer in the 1970s, which focuses on modeling human behavior in conjunction with feedback (1). This model is a linear representation (transition function) of the proportional-derivative regulator, incorporating a second-order delay and time (response) delay. Each constant within the model has a specific neurological or physiological interpretation. (Hess and Marchesi, 2009; Lone and Cooke, 2010; McRuer, 1974).

$$F(s) = \frac{Y(s)}{X(s)} = K \frac{(T_3 s+1)}{(T_1 s+1)(T_2 s+1)} = e^{-\tau s} \quad (1)$$

Here,

•K represents the pilot gain, which reflects the pilot's habitual response to a specific action. Additionally, it is associated with the ratio of the input to the output signal.

•T1 is the neuromuscular delay time constant, which quantifies the delayed response resulting from the pilot's neuromuscular system. This value ranges from 0.05 to 0.2 seconds and is independent of the intensity of training.

•T2 represents the delay time constant that characterizes the pilot's quickness and agility. It is linked to the execution of learned stereotypes and routine procedures. The value of T2 ranges from 0.1 to 5 seconds.

•T3 is the lead time constant, which is associated with the pilot's experience. It reflects the pilot's ability to anticipate potential situations. This ability, developed through training and experience, ranges from 0.2 to 15 seconds.

•τ represents the time constant that indicates the delayed response of the pilot's brain to a movement.

•s is the Laplace operator, commonly used in the analysis of dynamic systems in the Laplace transform domain.

To evaluate pilots’ reactions to simulated flight tasks, Boril et al. (2015) investigated pilots’ reaction times and ability to adapt to control dynamics by analyzing the data obtained from simulators. In the study, a flight scenario was defined on a flight simulator based on the originally developed X-plane (X-Plane, 2024) (altitude 2900 ft, speed 170 mph, pitch angle of approximately zero degrees). At a specific moment, the altitude was abruptly changed to 2600 ft, and the pilot was required to correct the altitude back to the original flight level of 2900 ft. A total of six student pilots, each with approximately 60-80 flight hours of real flight experience, were tested in this flight scenario. The altitude of each pilot was changed 10 times in succession, each time returning the aircraft to its initial flight state. The study empathized that pilots’ reaction times could improve with training and experience and pilots would adapt better to control dynamics with flight simulator training. The author stated that more studies were needed to develop research in this field and validate the methodology.

Haslbeck et al. (2014) researched how repetitive training and daily flight practice affected pilots' manual flight skills throughout their careers. The study was performed in collaboration with a leading European airline. Fifty-seven airline pilots with diverse levels of flight experience flew a 45-minute simulated landing scenario. Participants were divided into two groups: short-haul first officers (FOs) and long-haul captains (CPTs). The said groups represent high and low levels of practice and training, respectively. Pilots were evaluated in full-flight simulators in Airbus A320-200 or A340-600 configuration. The scenario required pilots to land manually after disabling the autopilot. Flight performance data were measured with the data recorder of the simulator in an objective way. The study results demonstrated that CPTs with low practice and training levels deviated more from ideal approach parameters. For instance, seven out of 27 CPTs (25.9%) failed to meet at least one of the allowed Instrument landing systems (ILS) deviation parameters. On the contrary, only two out of 30 FOs (6.7%) failed to meet these standards. The study findings showed that manual flight skills decreased over time and that regular practice was critical to maintaining these skills. High automation levels in long-haul operations may contribute to the deterioration of pilots’ manual flight skills.

In their study, Tanasković et al. (2020) determined that the difficulties experienced by pilots in transitioning from visual to instrument flight rules were the main cause of the accident that occurred with a Cessna 340 aircraft. This accident stressed the importance of pilots being prepared for sudden changes and challenging weather conditions. The study emphasized that transitioning from visual flight rules (VFR) to instrument flight rules (IFR) was a very complex process. Flight simulators come into play at this point. Simulators ensure that pilots experience crisis situations that they may encounter in real life in a safe and controlled environment. This helps pilots develop correct responses to emergencies and control their aircraft safely.

Liu et al. (2018) aimed to develop a system to assess pilots' flight performance based on Quick Access Recorder (QAR) data. This system was employed to assess, analyze, forewarn, and enhance pilots' flight performance by providing practical technical support to airlines in monitoring and controlling flight risks. The system developed employs a quantitative method to evaluate pilot performance. The evaluation model presented in the article is based on the statistical analysis of QAR data. This model ensures that one or more flight parameters are combined to objectively evaluate pilots’ flight performance.

Macchiarella et al. (2006) showed that student pilots practicing in the Flight Training Devices (FTD) required four more lessons to reach practical test standards for taxi and takeoff in comparison with students undergoing training in a real aircraft. McLean et al. (2016) concluded that flight simulators reduced the number of training hours before reaching the solo flight stage in the aircraft. The researchers found that total hours decreased from 16 to 14.7 hours, but the overall training time increased from 43 to 46.6 hours. A study by Goetz et al. (2012) yielded similar results. Whereas the experimental group that received training on a flight simulator required 77 days to be ready for solo flight, the group that started training in the aircraft required 86 days. The authors accepted that a sample consisting of only 12 students might have impacted the results adversely.

The study by Burki-Cohen et al. (2001) demonstrated that radio communication in flight simulators was usually performed by the instructor through role-playing and did not reflect the difficulties in the real-world environment. The authors stressed that realistic radio communication was one of the widely accepted deficiencies in flight simulators.

In the literature, desktop computer-based simulators are referred to as an alternative to expensive simulators without compromising student performance (l Reweti et al., 2017). Considering the rapid technological advancements in computers, there is an increasing interest in using flight simulation platforms, including Microsoft Flight Simulator (MFS, 2024), Lockheed P3D (Prepar3D, 2024), and X-plane (X-Plane, 2024). In addition to being an affordable platform, such simulators are also accessible to students even outside of the teaching field. A survey by Beckman (2003) showed that students and instructors found desktop flight simulators effective for homework and for helping students practice at their own pace, which increased their performance perceptions.

Recently, there has been considerable interest in applying augmented reality (AR) and virtual reality (VR) in flight training. Some studies have revealed that AR and VR benefit flight training and can improve learning since they allow users to fully immerse themselves in the virtual environment (Koglbauer et al., 2016). Furthermore, VR presents a faster learning process compared to traditional classroom approaches. Students who use VR can remember information longer and learn faster than those who learn with traditional methods (Pennington et al., 2019). Both AR and VR are promising techniques for transforming flight training since they can be utilized for the purpose of bridging the gap between classroom, simulation, and practical operations. The aforesaid techniques can be used for aircraft recognition and procedure training; thus, students can interact with the aircraft and understand processes better (Schaffernak et al., 2020).

Oh (2020) compared the perceptions of student and instructor pilots concerning flight operations using VR headsets. Participants thought that the VR simulator operated similarly or performed better than the traditional simulator and stated that it was more challenging to manage the cockpit systems and panels in VR than in the traditional simulator.

Furthermore, Dubois et al. (Dubois et al., 2015) stated that eye-tracking devices might be helpful as teaching and monitoring tools in flight training. These devices can identify students' scanning patterns so that instructors can intervene appropriately (Muehlethaler & Knecht, 2016).

3. Flight Simulators Used in Aviation

Although the first commercial pilot ground training devices emerged in the early 20th century, the actual usage of flight simulation began in the military field during World War II. The Link Trainer, the first commercially built flight simulator, gained significant recognition in 1934 following a series of accidents in the U.S. Army Air Corps, which highlighted the critical need for training pilots in Instrument Flying Conditions to prevent loss of life (BAATraining, 2024). Following World War II, flight simulation transitioned from the military to commercial aviation by the late 1950s (Schreiber et al., 2009). Simulators have been utilized in airline pilot training and evaluation since the 1950s. Nowadays, major airlines perform their recurrent training entirely on simulators and even use simulators in initial, transition, and upgrade training and certification processes.

At present, flight simulation training devices are utilized to train cockpit crew, maintenance personnel, and command and control personnel (Macchiarella et al., 2006). Additionally, these devices are utilized in the design and development of flight training programs (Wise et al., 2016) and accident investigations (Tydeman, 2004).

In the last four decades, flight simulators have contributed significantly to flight safety and have become indispensable for civil and military flight operations (Allerton, 2010; Chung, 2000). Training with FSTDs reduces the operating and maintenance costs of an aircraft fleet by reducing the number of training hours required in the air for a student to achieve a particular proficiency level (Smode, 1966). Flying a real aircraft involves coordination with various services, such as air traffic control and maintenance, as well as reliance on favorable weather and visibility conditions. These factors are mitigated through the use of FSTDs, which eliminate the need for such coordination and environmental dependencies. In this respect, FSTDs make a contribution to reducing pilot preparation time. From an environmental perspective, ground training devices are a more advantageous alternative to training in aircraft (Allerton, 2010; Vidakovic et al., 2021).

Additionally, the literature review demonstrates inconsistencies in the terminology applied to flight simulation training devices. This can lead to confusion in the analysis and application of existing research, as there is limited published material on the classification and broader application of FSTDs.

Due to the technical complexity of flight simulators utilized in pilot training worldwide, also known as Synthetic Flight Training Devices (FSTDs), standard terminology should be used everywhere. European Union Aviation Safety Agency (EASA) defined the following main terms and abbreviations in the document CS–FSTD(A) to eliminate this confusion (EASA, 2018).

A FSTD refers to a training device meeting the definition in Table 1.

Table 1. Categorization of Flight Simulators According to EASA (EASA, 2018)

FFS	FTD	FNPT	BITD
A	1	I	
B		II	
C	2	MCC	
D			

A Full Flight Simulator (FFS) is a complete, full-size replica of the cockpit of a specific type, brand, model, and series of aircraft. It incorporates all the necessary equipment and software to simulate the aircraft's ground and flight operations, including a force feedback motion system and a visual system that offers a view from the cockpit.

A Flight Training Device (FTD) is a full-size replica of the instruments, panels, equipment, and controls of a specific aircraft type, typically situated in either an open flight cockpit area or an enclosed cockpit. It includes all the necessary equipment and software to simulate the aircraft's ground and flight conditions but does not require a force feedback motion system or visual system.

A Flight and Navigation Procedures Trainer (FNPT) is a training device that simulates the flight cockpit environment, incorporating the equipment and computer software necessary to represent an aircraft or a group of aircraft in flight operations.

A Basic Instrument Training Device (BITD) is a ground-based training device that replicates the student pilot station of a specific aircraft class. It typically uses screen-based instrument panels and spring-loaded flight controls, offering a training platform primarily for the procedural aspects of instrument flight.

Other Training Device (OTD) refers to any training device, apart from a FSTD, used for training purposes where a full flight cockpit environment is not necessary.

EASA provides a comprehensive guide for the design, manufacture, testing, and operation of FSTDs. The document clearly defines the requirements, terminology, and test procedures to ensure that FSTDs accurately simulate aircraft in order to provide safe and effective flight training (EASA, 2018).

- Field of Application and Terminology
- FSTD Levels and Compliance
- Performance Tests
- Motion System
- Visual System
- Audio System
- Functions and Subjective Tests
- Verification Test Tolerances

Table 2 provides a general summary of FSTDs approved by EASA. An FFS is not required to replicate all physical aspects of flight; it only needs to meet the minimum standards set by the qualified authority. In (EASA, 2018), FFS levels are categorized as A, B, C, and D, ranging from the lowest to the highest level, respectively. These levels encompass the minimum requirements for visual, audio, and motion simulation systems, including factors such as flight controls responding to inputs, vibration simulation effects, and wind shear.

Flight simulators are devices that artificially replicate aircraft flight and various elements of the flight environment. They incorporate the equations that govern aircraft behavior, including how the aircraft responds to controls, aircraft systems, and external environmental factors such as turbulence, air density, precipitation, and clouds. Flight simulators can be further classified according to diverse criteria and areas:

According to their areas of use:

- Flight simulators for commercial flight training
- Flight simulators for military flight training
- Flight simulators for ab initio flight training
- Engineering flight simulators
- Skill test flight simulators (device)
- Flight simulators providing computer-based training (CBT)
- Usage of flight simulators for maintenance training

According to the purpose of training:

- Cockpit Procedures Trainer (CPT)
- Aviation Training Device (ATD)
- Basic Instrument Flight Training Device (BITD)
- Flight and Navigation Procedures Trainer (FNPT)
- Integrated Procedures Trainer (IPT)
- Flight Training Device (FTD)
- Full Flight Simulator (FFS)
- Full Mission Simulator (FMS)

According to the ICAO proficiency levels:

FSTDs are divided into seven types according to International Civil Aviation Organisation (ICAO) Doc. 9625:

- **Type I:** The first level including an enclosed or perceived cockpit/flight deck.
- **Type II:** It meets the same requirements as the first level but also includes Air Traffic Controller (ATC) environment simulation.
- **Type III:** It meets the previous requirements but also includes the runway condition simulation.
- **Type IV:** The level in question meets the same requirements as the previous levels. Additionally, it also involves features such as ATC environment simulation, external sounds, and voice control.
- **Type V:** The said level meets the same requirements as level IV, but features such as runway condition simulation, aircraft systems simulation, and dynamic control feel are added.
- **Type VI:** The level in question meets the same requirements as level V, but features such as expanded ATC environment simulation, motion system, and weather conditions simulation are added.
- **Type VII:** It is the highest level approved. It must meet all previous requirements, realized in a detailed and authentic way, as in the real aircraft.

4. The Importance of Flight Simulators in Pilot Selection

The costs of acquiring pilot certificates required by the Federal Aviation Administration (FAA) to work for airlines can reach a considerable figure, including flight time. The cost of a bachelor's degree can reach or exceed $100,000 at a private university, with additional costs for flight training added to this amount. Although pilot training programs at public universities are usually considerably less expensive, they still cost tens of thousands of dollars. It is estimated that costs for four-year university education with flight training can reach $50,000 per year. Other routes to obtain a pilot certificate, such as non-college flight schools, involve considerable costs for potential pilots. Despite the long-term earning potential, these costs are thought to adversely impact enrollment in pilot training programs (Croft, 2015)

Table 2. FSTD classification requirements according to EASA (EASA, 2018)

FSTD Type	Flight deck/cockpit environment	Simulation capabilities	Equipment and software specifications	Visual system	Force cueing motion system
FFS	A full-size replica of a flight deck or cockpit refers to a complete, scaled reproduction of the cockpit of a specific aircraft type, make, model, and series. This replica includes all relevant instruments, controls, and equipment found in the original cockpit.	Represents the aircraft in both ground and flight operations, simulating the behavior and functionality of the airplane during various phases of flight, as well as its operations on the ground.	Includes a complete set of all necessary equipment and incorporates computer software programs required to accurately simulate the aircraft's systems and operations, both on the ground and in flight.	Required to provide a view from the flight deck or cockpit, simulating the external environment during flight operations.	Required
FTD	A full-size replica of a specific aircraft type's instruments, equipment, panels, and controls refers to a complete, detailed reproduction of the cockpit's interior layout, including all functional components found in the original aircraft, such as flight instruments, control panels, and flight controls.	Represents the aircraft in both ground and flight conditions, based on the systems installed in the device, simulating the behavior and functionality of the aircraft according to the specific equipment and software within the training device.	Includes an assembly of all necessary equipment and incorporates computer software programs required to simulate the aircraft's systems and operations, enabling realistic training in both ground and flight conditions.	Not required	Not required
FNPT	The flight deck/cockpit environment	Represents an aircraft or a class of airplanes in flight operations, ensuring that the systems function as they would in a real aircraft, providing a realistic simulation of aircraft behavior and performance during flight.	Includes an assembly of all required equipment and computer software programs, which together simulate the aircraft's systems and operations, enabling accurate representation of flight operations.	Not required	Not required
BITD	The student pilot's station	Provides, at a minimum, the procedural aspects of instrument flight for a specific class of airplanes, focusing on training for navigation and operation under IFR.	Not explicitly specified, but likely involves the use of screen-based instrument panels and spring-loaded flight controls to simulate the aircraft's systems and response during training.	Not required	Not required

Since pilot selection has substantial costs, it is essential to use robust processes based on scientific foundations, even if there is a limited pilot supply relative to demand. The risk of accidents is the most evident cost of wrong choices. For instance, deficiencies in basic piloting skills, e.g. understanding how to respond to an impending or existing aerodynamic stall, have played a role in accidents, including Air France 447 and Colgan 3407. One of the causes of accidents is the over-reliance on computerized flight systems by airlines and aircraft manufacturers, which has been indicated to impair pilots' ability to operate the systems in emergencies manually (Oliver, 2017). Selecting pilots with better piloting skills can increase the margin of safety. On the contrary, not eliminating pilots with weak piloting skills can increase risks to property and safety. Such risks to property and safety increase the significance of sound selection procedures. Another evident cost is the training time needlessly lost by the mainline or regional carrier. Investments in pilot training are basically avoidable costs for the employer in case of the failure of that pilot. A scientifically based pilot selection process can decrease such avoidable costs (Broach et al., 2019).

As specified by Damos (2014), two factors have complicated pilot selection in the past two decades. First, despite over 100 years of research on pilot selection, the dissemination and implementation of research findings in pilot selection worldwide has been a continuous problem. A portion of the problem lies in communicating psychological and statistical concepts, data, and recommendations in a language that corporate executives can understand, trust, and utilize. Second, the supply of pilots has shifted significantly, at least in the United States of America (U.S.) market and probably in other non-U.S. employment markets. Former military pilots have been a dominant source from World War II until the early 1980s. U.S. military pilots represent the product of an intensive, rigorous, and continuous elimination process. Those who have transitioned from military service to civilian airlines have successfully passed that elimination process. In selection terms, they are pre-selected regarding job-related factors, including emotional stability, cognitive ability, and the piloting skills displayed. However, nowadays, former military pilots constitute only a part of new pilots in the U.S. Most pilots hired in the last two decades have not undergone the same level of examination as that applied to aspiring military pilots. Moreover, it can be said that entry into civilian flight training programs nowadays is based more on the "wallet test" than all other factors. Consequently, variability in factors including cognitive abilities, attitudes, personality, and piloting skills among civilian pilot candidates is likely to be higher than before. This greater range of variability reinforces the need to enhance pilot selection processes to enable the recruitment of pilots at the upper end of the knowledge, skill, and ability distribution.

Time is usually a significant constraint in pilot selection. Funding for both the improvement and management of a selection process has almost always been a problem. Another difficulty is accessing and acquiring relevant predictive and job performance data for validation studies. The fourth difficulty is the balance between validity and equity (Pyburn et al., 2008). The final difficulty is candidates' reactions to the selection process. Issues, e.g. procedural fairness, perceived validity, and outcomes, can cause candidates' positive or negative reactions, which can impact an employer's reputation and ability to attract qualified candidates, especially in tight-knit communities such as pilots (Truxillo et al., 2009).

The common characteristics of pilot selection systems involve age, education, English proficiency (in non-English speaking countries), and usually a requirement to pass mathematics and English courses successfully. Interviews are also very common (Broach et al., 2019). A 2012 research report conducted by International Air Transport Association (IATA) on airlines reached the following pessimistic results: "Despite the clear benefits of an appropriate pilot selection process, the results demonstrate that only a small number of airlines have a structured and scientifically based specific selection system" (IATA, 2019). There are generally two primary models in civilian pilot selection. The Lufthansa model performs a strict selection process from the beginning, which leads to less elimination during the training process. The alternative model involves a superficial selection process from the beginning, which allows for more elimination during the training process (Broach et al., 2019).

5. Conclusions and Recommendations

The aviation industry will face a considerable pilot shortage in the following years. It is essential to adopt innovative training technologies and approaches to meet the training needs of the new generation of pilots. Collaboration between universities and airlines is of critical importance to ensure that the said technologies are effectively implemented and that future pilots are trained in the best possible way.

Flight simulators are an indispensable part of the program implemented to ensure safe and efficient pilot training. The importance of well-designed simulators and accompanying modern training programs in effective pilot training should not be ignored. Safe and efficient training provided using FSTDs is among the basic components of military, commercial, and general aviation training. In comparison with live training, increased safety and decreased costs of pilot training are the most important advantages of ground training devices.

The current work shows the importance of flight simulators in pilot training and evaluation by reviewing studies in the literature in detail. Under the information obtained, the advantages and disadvantages of flight simulators in pilot training can be listed as follows:

Advantages:

- **Safety:** Flight simulators allow pilots to experience crisis situations and implement emergency procedures without taking risks.
- **Cost:** Flight simulators are considerably more economical in terms of purchasing, operating, and maintenance costs in comparison with real aircraft.
- **Flexibility of Use:** Flight simulators can be used 24/7, regardless of weather conditions.
- **Training Efficiency:** Flight simulators increase training efficiency by providing the opportunity to repeat and analyze particular flight conditions and emergency scenarios.

Disadvantages:

- **Realism:** Flight simulators may not perfectly imitate the real flight experience.
- **Psychological Factors:** Pilots may not feel the stress and pressure in the simulator environment as they do in real life.

Consequently, flight simulators are essential tools helping pilots improve their skills, learn crisis management procedures, and contribute to safe flight operations. Performance analysis based on simulator training should be conducted. Simulator trainings covering the routes that pilots fly can also be beneficial in terms of real scenarios Airlines must implement strategies such as additional simulator training and mixed-fleet flights to help pilots maintain their manual flying skills. On the other hand, designers must explore adaptive automation approaches allowing for more flexible task sharing between humans and automation.

Abbreviations

AR	Augmented Reality
ATD	Aviation Training Device
BITD	Basic Instrument Training Device
CBT	Computer-Based Training
CPT	Cockpit Procedures Trainer
CPT	Captain
EASA	European Union Aviation Safety Agency
FAA	Federal Aviation Administration
FFS	Full Flight Simulator
FNPT	Flight and Navigation Procedures Trainer
FMS	Full Mission Simulator
FO	First Officer
FSTD	Flight Simulation Training Device (FSTD)
Ft	Feet
FTD	Flight Training Device
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IPT	Integrated Procedures Trainer
Mph	Mile Per Hour
OTD	Other Training Device
PPL	Private Pilot License
QAR	Quick Access Recorder
US	United States of America
VFR	Visual Flight Rules
VR	Virtual Reality

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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A Sectoral Study on Energy Production from Human Movement at The Airport

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Abstract

Throughout the history of civil aviation, developing technology, changing demands and needs of passengers, expectations of stakeholders, and increasing awareness about sustainability have changed the structure of airports and the opportunities they offer. Increasing awareness about sustainability has directed humanity towards non-conventional energy sources.
Human energy, which is among the non-conventional energy sources and whose source is concentrated in airport terminals, constitutes the focus of the study. The main purpose of the research is to determine the conversion methods of kinetic energy arising from passenger mobility into electrical energy at airports, to create environments in which passengers participate in energy production in terminal areas, to evaluate the perspectives of aviation professionals on post-modern energy production in the context of passenger mobility and to create the first step in raising awareness on the subject.
The data that forms the basis of the research was obtained through interviews with aviation professionals through vignettes prepared for this purpose. In the light of the literature and global current practices, two separate vignettes were created about the methods of generating electricity by pedalling a bicycle and applying pressure to the ground in children's playgrounds in the terminal buildings, both to raise awareness about sustainability and to strengthen the image of the airport operation. The data obtained from the interviews using these vignettes were evaluated with an inductive approach and content analysis.
As a result of the research, postmodern electricity generation methods were discussed with the help of professionals' observations and experiences, the themes of muscle strength and piezoelectric principle application evaluation were found and it was revealed that the advantages of these themes came to the fore.

**This study is derived from the master's thesis titled Sustainable airport management: A research on the perception of energy production from human movement*

1. Introduction

The increasing consumption of conventional (non-renewable) energy resources creates a global energy crisis and environmental pollution, and civil aviation activities, with their intensifying operations day by day, cause the crisis and pollution in question. For this reason, the importance of the concept of sustainability is increasing in the civil aviation sector, as in every sector, and stakeholders such as airport operators, airlines and ground service providers frequently include sustainable practices in their operations. Stakeholders who integrate non-conventional (renewable) energy sources into their business processes and aim to reduce resource use by producing energy need more innovative investments over time. As sustainability becomes more and more prevalent in people's lives, obtaining energy from human activities is gaining popularity day by day. In line with the literature review and research, it has been determined that manpower energy, one of the non-conventional energy sources, is relatively weak in the field of civil aviation. In order to create the first step of awareness about manpower energy and to evaluate expert perspectives, two separate vignettes (short stories) in which the existing manpower energy is effectively used in airport terminal buildings were directed to aviation professionals and interviews were held with them. The data obtained as a result of the interviews were evaluated with content analysis.

2. Literature Review

The rapid increase in energy demand is a major concern in recent years. Environmental problems caused by existing energy sources such as climate change and global warming force human beings to use non-conventional (renewable/alternative) energy sources (Mekhilef, Saidur and Safari, 2011, pp. 1777-1778).

While oil, natural gas, coal and nuclear energy constitute conventional energy sources, solar, wind, biomass, water power and human energy constitute non-conventional energy sources (Şenpınar, Gençoğlu, 2006, p. 49).

Non-conventional energy sources also include human power (Bidwai, Jaykar, Shinde, 2017, p.424).

Harvesting energy produced from muscle power and piezoelectric materials has an important place among human power-based non-conventional resources (Dokur et al., 2014, p.53).

Below, data obtained from the literature on muscle power and electricity generation with piezoelectricity are given.

Electricity Generation with Muscle Power

Studies have been carried out on producing energy by pedaling a bicycle since the 1950s, and developments are being made in the production and storage of energy day by day (Enerji Portalı, 2023).

In their study, Duraklar, Şen and Atasoy (2013) aimed to store the energy spent by customers in gyms by converting it into electrical energy in order to use it effectively and prevent it from being wasted.

In their study, Portakal, Adıgüzel and Sayar (2014) produced electrical energy by pedaling and stored this energy by transferring it to the battery and then used it to charge mobile phones and tablet computers. Thus, mechanical energy that could not be used effectively and wasted was transformed into electrical energy.

In their study, Bidwai, Jaykar, Shinde (2017) focused on obtaining energy from gym bikes in gyms because exercising in the gym has an important place in modern life and people's interest in gym exercises is increasing.

In their study, Zaman et al., (2017) aimed to collect electricity by using the energy obtained from human movement through the gym bike.

Yadav et al., (2018) believed that more effective use of manpower could be achieved with properly designed mechanisms and stated that the most suitable and effective technology to use manpower efficiently was bicycle technology.

Electricity Generation with the Piezoelectric Principle

The concept of piezo, which means pressure in Greek, was introduced by French scientists J. and P. Curie in the 18th century. The piezoelectric feature converts the mechanical energy in the electric field into electrical energy as a result of the pressure applied to the materials (Çalışır, Akçay, Sürmeli, 2020). The foundations of the application are considered to have been laid by Hasler, who positioned a piezoelectric implant in the ribs of a dog. Thanks to the positioned implant, 17µW of energy was produced. Starner placed the piezoelectric polymer in the sole of the shoe, thus creating the basis of wearable energy. He predicted that an individual weighing approximately 50 kilograms could produce 5 W electricity as he took a step (Tüfekçioğlu, 2014). Khaligh, Zeng, Zheng (2009); Wei, Hu, He, (2013); Aslan, Bilgin and Erfidan (2016); Khan et al., (2019); Qian, Xu, Zuo (2019), authors working on human power-based piezoelectricity, developed prototypes and created various simulations.

In the literature, the usage areas of electricity generation with the piezoelectric principle in road, railway and air transportation are included.

Highway Transports

The mechanical energy available on highways can be used for various purposes, such as powering traffic lights, monitoring the structural health of roads, and providing energy to self-powered vehicle weighing systems.

Dokur et al., (2016) developed a prototype of an electricity generation system using piezoelectric materials that benefit from vibration, intended to be applied in road and railway transportation.

In their study, Kim, Shen and Ahad (2015) simulated and tested two piezoelectric energy harvesting units that produce voltages ranging from 5 to 20 V.

Chen et al., (2017) designed an energy harvesting system consisting of a vibration-induced piezoelectric circuit for speed bumps on the road.

In their article, Papagiannakis et al., (2017) aimed to develop several piezoelectric prototypes that can collect energy from the movement of road traffic.

Jasim et al., (2017) aimed to develop a new piezoelectric transducer design with optimized geometry for harvesting the energy generated under vehicle load on the highway.

In their study, Li et al., (2018) conducted tests to determine the piezoelectric generating capacity of the road pavement and obtained a maximum voltage of 65.2 V.

Roshani et al., (2018) presented the results of a theoretical and experimental study aiming to develop a vibration-based road energy harvesting system.

Railway Transportation

The mechanical energy available in railways can be used for various purposes, such as powering railway structural health monitoring systems and providing energy to sensors and automatic warning systems.

Nelson et al., (2009) found the solution to the search for a long-term, low-maintenance power source for remote railway systems in the piezoelectric principle, since the railways, a significant part of which is located in relatively remote areas, are weak in terms of warning light systems due to the cost of the electrical infrastructure.

Pasquale, Soma, Fraccarollo (2012) converted the mechanical vibrations of railway vehicles into electrical energy through a piezoelectric energy collector. The harvested power was used to provide structural tracking energy in railway vehicles.

In their study, Tianchen et al., (2014) focused on collecting energy from rail vibration to power wireless sensors on the railway. Considering that the rail has vibration energy, they proposed a new method to harvest energy based on the piezoelectric effect.

In their study, Pourghodrat et al., (2014) aimed to collect energy from existing traffic to provide electricity to automatic warning systems as well as sensors in order to increase safety in railway transportation systems. They have shown that piezoelectric devices are applicable for low power applications in railway transportation systems.

Wang et al., (2015) examined energy harvesting from railway systems in their study.

In their study, Gao et al., (2016) proposed a 200 mm × 170 mm × 80 mm piezoelectric generator to collect the energy arising from the rails on the railway. They used a hydraulic system with an excitation force of 140 kilonewtons to simulate the situation.

Yang et al., (2021) presented an efficient railway-induced piezoelectric energy harvester to harvest energy from railway vibration and established the corresponding model. The proposed piezoelectric energy harvester was evaluated by laboratory experiments and theoretical analysis.

Air Transportation

Airports are structures built on a larger scale and more sophisticated in terms of both infrastructure and information structure, aiming to be the most comprehensive air transportation service providers connecting countries internationally. When looking at the daily operations of an international airport, it becomes clear that energy consumption is very high. Additionally, relying on fossil fuels to power airports and run operations on a daily basis lead to many negative socio-environmental impacts. To date, several of the world's leading international airports have begun to adopt renewable energy, focusing on solar energy, towards reducing fossil fuel consumption and greenhouse gases.

Inspired by thinking differently since the adoption of solar energy at Kuala Lumpur International Airport (KLIA) in 2014, Chew et al., (2017) proposed another adaptation of renewable energy piezoelectric technology to KLIA as a feasibility study.

In their study, Agarwal and Sharma (2014) presented a piezoelectric system to be used to harvest vibration energy from airport runways.

Currently, there is a need to use alternative energy sources in passenger terminals of airports and railways around the world. Dhingra et al., (2012) examined the fundamentals of piezoelectricity in energy harvesting and carried out studies on obtaining energy from shoes, applications in terminals, and providing lighting from pedestrian traffic.

Kavirat (2017) proposed piezoelectric floors for use in densely populated airport terminal areas such as check-in counters, passport control, duty free and boarding gates.

Salim, Abdulrazig (2020) mentioned in their studies the importance of providing secondary solutions in energy production compatible with the environment and economy, due to the existence of constant energy demand, high costs and depletion of natural resources.

The authors, who carried out a theoretical study on generating electricity using piezoelectric materials in order to obtain sufficient and clean electrical energy, gave examples of the applications of piezoelectricity in various fields and also mentioned the use of piezoelectric systems at points of passenger traffic in airport terminals.

Airports want to create enjoyable experiences for their passengers. Heathrow Airport wanted to offer its visitors a unique, unforgettable, innovative and exciting travel experience and placed piezoelectric floors under the passengers' feet. They benefited from the high passenger traffic of one of the busiest terminals. Passengers can generate energy for lighting screens while walking on the walkway in the relevant corridor (Pavegen A, 2023).

The 'Power Floor' project was put into service at Heathrow Airport with the interactive corridor concept. Located at Heathrow Airport Terminal 3, the floor consists of a panel of 100 colored tiles that capture the kinetic energy from passengers' steps and convert it into electricity. More than 5,000 passengers pass through the corridor connecting the Terminal 3 waiting area to the departure gates every day. This mobility converts passengers' steps into electricity for 18 hours a day, providing kinetic energy that illuminates the area. The airport management has very positive thoughts about the possibilities offered by the relevant technology as a sustainable energy source for the future (Bilbao, 2023).

Trying to create a pleasant travel experience based on sustainability that its passengers will remember, Abu Dhabi Airport has built a 16-meter energy-producing walkway in the terminal, utilizing the piezoelectric principle (Pavegen B, 2023).

3. Methodology

3.1. Aim of Research

Although there is an incentive and tendency to use non-conventional energy sources in many sectors, this use is also valid for operations in the civil aviation sector.

The aim of the study is to create environments where passengers participate in energy production in terminal areas by determining the conversion methods of kinetic energy arising from passenger mobility at airports into electrical energy.

In line with this purpose, the study aims to evaluate the perspectives of experts on post-modern energy production in the context of passenger mobility through prepared short stories.

For this purpose, the research question was determined as.

- How can sustainable energy production be contributed by using muscle power and piezoelectric principle in airport terminal buildings?

In order to achieve this goal, the importance of generating electricity with muscle power and the piezoelectric principle based on human mobility was emphasized, potential sustainable electricity generation methods that could be used in terminal buildings were directed to experts through vignettes, and suggestions were made by evaluating the validity and applicability of these methods.

3.2. Limitations of the Research

The basis of the research was to use the electricity produced by muscle power and the piezoelectric principle to power the computers at the check-in counters in the terminal or to provide illumination of certain areas. As a result of the research and interviews conducted, it has been concluded that these gains will not be at the desired level. The vignettes, which were created primarily to raise awareness and image, were directed to participants who continue their professional lives in the field of civil aviation and their opinions were sought. Interviews were held with seven professionals.

3.3. Research Method

The data obtained as a result of semi-structured interviews conducted after the vignettes created for the research question are transferred to the participant will be qualitative data. For this reason, qualitative research method was adopted in the study.

There are two basic approaches to analyzing qualitative data. These approaches; deductive approach and inductive approach. In the deductive approach, a structure or predetermined framework is used to analyze data. The researcher imposes his or her own structure or theories on the data and then uses these to analyze interview transcripts. This approach is useful in studies where researchers are already aware of the answers they obtain from interviews. The inductive approach involves analyzing data with little or no predetermined theory, structure, or framework, and uses the actual data itself to derive the analysis structure. Interview transcripts are descriptive of the study, but they do not provide explanation. It is the responsibility of the researcher to explore and interpret the collected data. The process of thematic content analysis, where data is analyzed manually or using computer software, is essentially the same. The researcher reads each participant's statement and makes notes in the margins with words, theories, or short phrases that summarize what they expressed. This is often called open coding. The aim is to provide a summary phrase or word for each element present in the participant's statements. Then, the researcher categorizes the words that summarize the participants' statements. The codings are collected in category lists. A list of up to twelve categories can be prepared. Category lists are also reduced and their final version is created. As a result, the researcher obtains an organized data set.

When the literature is examined, it is seen that there are different opinions about sample size in qualitative studies, and the largest sample size in the relevant opinions is 50. Some opinions suggest that a sample size of 10 people is sufficient for qualitative studies if sampled from a homogeneous population (Sandelowski, 1995). According to Creswell (1998), a sample of 20-30 people is large enough to create a theory. Marshall et al. (2013) think that a sample of 20 people is small, a sample of 40 people is large, and a sample of 30 people is sufficient. Sandelowski (1995) states that a sample size of 50 people is too large a sample for a qualitative study. In addition, the sample size cannot be determined before the research, and it is argued that the research should be continued until data saturation is reached (Blaikie, 2018; Sim et al., 2018). According to Sim et al., (2018), the sample size should be in the range of 5-35 people for theory development research and 4-30 people for a case study.

If it is qualitative research conducted with very large data sets, computer programs may be more useful in the analysis process. However, researchers who want to use relevant programs and software must first receive appropriate training.

Analysis of qualitative data, of course, involves interpreting study findings. However, this process has some subjective features. There is a common belief among social scientists that there is no objective and definitive view of social reality. This situation causes the confirmability problem of qualitative data analysis. Therefore, there is a need for qualitative researchers' analyzes to be verified or approved by a third party. It is argued that verification and validation will reflect the analysis more rigorously and unbiasedly. Analyzes can be verified and validated by participants or peers. Analyzes made during participant verification are presented to the participants again for their approval. In peer validation, another qualitative researcher is asked to evaluate the analysis of the data. Participant verification involves going back to respondents and asking them to read the data analysis carefully to confirm or refute the researcher's comments. Although this arguably helps improve theme and theory development, the process is quite time-consuming and unless it occurs relatively soon after data collection and analysis, participants may have changed their perceptions and views due to the passage of time. Despite all the debate, there is no definitive answer regarding validity in qualitative analysis. However, all data collected needs to be analyzed in detail to ensure that the analysis process is systematic. There are two approaches to writing down the findings of qualitative research.

The first is called the traditional approach and is to report the main findings under each main theme or category, using appropriate verbatim quotations to illustrate these findings. The findings are presented in a separate discussion section. In the second approach, referred to as the combined approach, the discussion is included in the findings section. It is not available in a separate section (Burnard et al., 2008).

3.4. Participants and Data Collection Method

The participants of the research are professionals in the field of civil aviation. Vignettes prepared as a data collection tool were presented to the participants who had experience in airport operations, developed sectoral knowledge, and who were also airport customers and airline passengers, and then their opinions were taken in order to create a general idea in the light of their experiences.

Although vignettes were first used in quantitative research by psychologists in North America, they are also used in qualitative research. As vignettes are preferred in literature, they have become important for qualitative research.

According to Finch (1987), vignettes are short stories created in specific situations that require the interviewee to respond. Stories have aspects of the context and enable certain forms of open-ended questions that are specific to the situation. According to Azman and Mahadhir (2017), stories are short depictions of typical scenarios that aim to find answers that will reveal values, perceptions, impressions and accepted social norms. According to Hughes (1998), vignettes are called concrete scenarios or short stories written about certain situations. The use of vignettes as a data elicitation technique encourages the expression of participants' perceptions, ideas, beliefs, and attitudes as they respond to or comment on concrete scenarios and situations as depicted. In qualitative research, vignettes are often used in conjunction with several other methods, such as interviews.

According to Tasar (2006), vignettes have the advantage of collecting in-depth information, especially in qualitative and small sample studies. In social sciences, vignettes are data collection tools that can be designed based on the opinions of experts in the field or on experienced situations. It should be noted that vignettes are not case studies and should be limited to 50 to 250 words and should not be too long. They should convey the situation in a simple and understandable way (Kemer and Aslan, 2022).

According to Campbell (1996), there are three steps to create vignettes. The first step is to determine the subject of the vignettes and to whom they will be applied. Next comes the creation of realistic and understandable vignettes for the people to whom the vignettes will be applied. The last step is to conduct a pilot study to test whether the vignettes are understandable, clear and appropriate to the target.

When creating vignettes, six factors should be taken into consideration: detail, understandability, credibility, environmental factors, structure and format. Details, although not numerous, should be given in a way that supports the vignette and helps it come to life in the person's mind better. Vignettes should be understandable, reflect realistic situations and be believable, describe the environmental factors of the situation well, and have a structure appropriate to the target. Although vignettes are mostly presented in written format, they can also be presented in the form of video or audio files (Kaya and Kaya, 2013).

In the study, firstly, the topic and the research question mentioned above were decided. Then, the appropriate vignette type was decided. Afterwards, vignettes were created. The vignettes created at this stage - based on the vignette creation steps of Campbell (1996) - were presented to doctoral students and their comprehensibility was tested. Then, opinions about the vignettes were received from two assistant proffesor, one lecturer and two research assistants. With all the feedback obtained, the options were revised and made ready for use. It was studied with purposeful sampling and maximum diversity was aimed. Qualitative data were collected through semi-structured interviews. Finally, the data obtained was analyzed with inductive content analysis.

Below is the first vignette created and directed to participants.

Vignette 1: Generating Electricity by Pedaling a Bicycle

In certain areas of the airport terminal buildings, there is an area with bicycles that produce electrical energy as they are pedaled. Mobile phones, laptops and tablets can be charged by using a bicycle in the area. By using the bike, the passenger will be able to use his own muscle power to power his electronic devices, while doing so will not have a negative impact on the environment and will also provide the mobility required for a healthy life. During a portion of the total travel time, the passenger will perform a different activity and have a more enjoyable time. In order to encourage the use of the relevant bicycles, the passenger participating in the application will be provided with a discount coupon from contracted food and beverage service providers and the parking service. The amount of discount offered with coupons will increase in direct proportion to the duration of using the bike. During a half-hour cycling period, you will receive a '5% discount coupon' valid for food and beverage service providers, and a 'free use of 15 minutes of parking time' valid for parking facilities. Passengers will have the right to use this discount again at the same airport within one year.

• Based on the vignette above, which of the following options would you choose?

a) It would be an application that would interest me and support it. I would definitely take the time to participate.

b) It would interest me, but I would not spend time on application.

c) I wouldn't be interested. I would not want to spend time on this application during my time at the airport.

• Can you explain in a few sentences why you choose the option you chose?

Vignette 2: Piezoelectric Floor Application in Children's Playgrounds in Terminal Buildings

In order not to waste the energy that children already have; piezoelectric systems have been installed on the floors of playgrounds in certain areas of the airport terminal buildings.

Thus, points were created where the available energy that could not be used effectively was harvested. The passenger will want to benefit from the children's playground in the terminal buildings, aiming to ensure that the accompanying child passenger has a more enjoyable time during the total travel time. In areas where entertainment opportunities are offered enriched with various toys, children will contribute to electricity production as they move and apply pressure to the ground. The energy obtained from the movement of children will power and operate the LED strip lighting equipment in the area and will flash in different colors. Thus, by seeing the energy they produce being used, children will begin to gain environmental awareness at an early age, and their awareness of the subject will begin to develop.

• Based on the vignette above, which of the following options would you choose?

a) It would be an application that would interest me and support it. I would definitely take the time to participate.

b) It would interest me, but I would not spend time on application.

c) I wouldn't be interested. I would not want to spend time on this application during my time at the airport.

• Can you explain in a few sentences why you choose the option you chose?

3.5. Analysis of Data

The process of analyzing qualitative data includes classification and interpretation in order to develop evaluations to gain meaning from the collected data. Analysis enables obtaining logical meanings from the essence of the data by reducing the amount of data obtained (Çelik, Baykal and Memur, 2020).

According to Creswell (2002), qualitative data analysis is classified in six steps. The six steps in question are; preparing and organizing the data for analysis, coding the data, creating themes, reporting the findings, interpreting the findings and testing the accuracy of the findings.

According to Wolcott (1994), qualitative data analysis is divided into two: descriptive analysis and content analysis. Content Analysis is an in-depth analysis of the data obtained and enables the creation of themes. The basis of content analysis is to integrate similar data into some themes and interpret them for the target audience.

In the research, inductive content analysis was performed to reveal the concepts and relationships of the data obtained by coding, dividing into categories and themes.

3.6. Compliance with Ethical Rules

An ethics committee application was made for the research on 13.04.2023, numbered E-60850919-300-2300020021. The ethics committee application numbered E-87914409-050.03.04-2300025331 was examined by the Social and Human Sciences Scientific Research and Publication Ethics Committee on 16.05.2023. The research was found ethically appropriate.

4. Findings and Discussion

Within the scope of the research, professionals in the field of civil aviation were interviewed and findings were presented. Participants were given codes as P1, P2, P3, P4, P5, P6 and P7. Demographic information of the professionals participating in the research is given below.

Table 1. Demographic Information of Participants

Participant	Gender	Age	Organisation - Flight Frequency
P1	Male	18-28	Airline- 15 times a year or more
P2	Female	18-28	Others- Less than 5 per year
P3	Male	28-38	Ground Handling Service- 15 times a year or more
P4	Male	28-38	Ground Handling Service- 5- 10 times a year
P5	Female	28-38	Others - Less than 5 per year
P6	Female	18-28	Airline- Less than 5 per year
P7	Female	48+	Others- 15 times a year or more

Table 1. contains information about the gender, age, organization they work for and flight frequency within a year of the participants coded as P1, P2, ... P7. Participants, in the civil aviation sector, work in ground handling services, airline companies and others. The participants, who had the opportunity to closely observe passengers' wishes and needs and hear their opinions, are experienced experts who follow current developments on sustainability, airport and environmental issues, and have been to various international airports.

Table 2. Frequency Values of the Options Marked According to the First Vignette

Option	Frequency
It would be an application that would interest me and support it. I would definitely take the time to participate.	3
It would interest me, but I wouldn't take the time to practice it.	4
I would not be interested. I would not want to spend time on this application during my time at the airport	0

As seen in Table 2., no participant chose the "I would not be interested." option for the first vignette titled Electricity Generation by Pedaling a Bicycle. This shows that the vignette attracts the attention and interest of the participants. The option "It would interest me, but I would not take the time to practice it " (f=4) was the most preferred option. Then, the option ‘It would be an application that would interest me and support it’ was preferred.

Some of the prominent expressions of the participants about the first vignette are given below.

'Passengers need to charge their phones and computers at airports. It is a great experience that they do this in an environmentally friendly way with their own actions. Based on my observations, I think that such an application could be widely used, for example, at Istanbul Airport. Because it is an airport where transit flights take place very frequently.' P5.

'It would be an application that would interest me and support it. I would definitely take the time to participate. As a result of my observations on flights and in the terminal, I think that the application would be more preferred if the discount coupons were a little more encouraging.

In 2013, I won a t-shirt with a similar application at Bangkok Airport. I've kept it ever since.' P3.

'I found the discount amounts generally low. When I think about the passenger profile, I believe that passengers should be encouraged a little more if intensive usage is desired. Especially when we target the young generation, the application may be more attractive if there is the opportunity to watch some content on a screen while cycling.' P1.

Table 3. Frequency Values of the Options Marked According to the Second Vignette

Option	Frequency
It would be an application that would interest me and support it. I would definitely take the time to participate.	7
It would interest me, but I wouldn't take the time to practice it.	0
I would not be interested. I would not want to spend time on this application during my time at the airport	0

As seen in Table 3., for the second vignette titled Piezoelectric Flooring Application in Children's Playgrounds in Terminal Buildings, all participants (f = 7) chose the option " It would be an application that would interest me and support it. I would definitely take the time to participate."

Some of the participants' prominent statements about the second vignette are given below.

'While the existing children's playgrounds are already an activity area that I like, especially because it brings together children from different cultures, the fact that it serves such a purpose has created extra positive ideas. Instilling and developing awareness in children at a young age through play will be more effective and memorable. The fact that children do not waste their energy and do not get bored while waiting for the plane shows the versatility of the application. When you look at it, it is actually an application that will raise awareness of adults as well.' P6.

'It is an application that I think will be very effective in broadening children's horizons and developing their imagination.' P4.

'This will definitely be an application that a passenger traveling with his/her child will be interested in. Playgrounds will also be effective in helping the child release his energy and have a calmer flight. While it is a remarkable practice for the child, I think it will also raise awareness for their parents.' P2.

'While the journey is a stressful process for the passenger, it can become an even more stressful process for the child. Based on my flight operation experiences, I have observed many times that children become restless during this process. Flights create some physiological imbalances in children... Especially in terms of children having fun and spending time with toys - even if they do not produce energy - it is an area that will relax parents and children and make the journey more comfortable. In addition, it will be interesting for children as it contributes to electrical energy. In addition, I believe that the earlier sustainability awareness is ingrained in the child, the more active role it will play in the future. Although there is a possibility that younger children may not understand the process, awareness is created in the first place. Even if the relevant acquisition is not achieved at that moment, it will develop when the child grows up.' P5.

Below are the codes based on the quotes from the interviews held regarding the first vignette titled Electricity Generation by Pedaling a Bicycle and the second vignette titled Piezoelectric Flooring Application in Children's Playgrounds in Terminal Buildings.

As a result of the interviews of the first vignette, insufficient discount, more incentives, sweating, fatigue, insufficient time, interesting, rush to catch up, experienced, higher participation in domestic flights, an application that will give pleasure during the stressful journey, environmentally friendly, fun, healthy life, sustainability, tiring travel process and innovative application codes were created.

As a result of the interviews of the second vignette, the need for sufficient time, the hygiene provided, attractive, interesting, the child's energy boost, the child being calm during the flight, attention-grabbing, awareness raising, parental awareness, positive perspective towards the airport, an effective application on children, stressful travel process, even more stressful travel process for the child, physiological imbalance and unrest, a pleasant practice, comfortable and relaxing, sustainability, intercultural interaction, effective purpose, awareness formation, versatility codes were created.

Table 4. Main Category (Theme) and Categories of the First Vignette

Main Category (Theme)	Categories	Temporary Categories
Human movement-based energy production evaluation of possible muscle power applications suitable for in airport terminal	Advantages	Attractive application Sustainable application
	Disadvantages	Insufficient earnings Physical negativities Time limit

In Table 4., as a result of the interviews for the first vignette, the categories were determined as advantages and disadvantages. The theme has been determined as human movement-based energy production evaluation of possible muscle power applications suitable for in airport terminal.

Table 5. Main Category (Theme) and Categories of the Second Vignette

Main Category (Theme)	Categories	Temporary Categories
Human movement-based energy production evaluation of possible piezoelectric principal applications suitable for in airport terminal	Advantages	Attractive application Calming down Having consciousness Increased business image Active application Sustainable application Various achievements
	Disadvantages	Time Limit

In Table 5., as a result of the interviews for the second vignette, the categories were determined as advantages and disadvantages. The theme has been determined as human movement-based energy production evaluation of possible piezoelectric principal applications suitable for in airport terminal.

When the findings of the first vignette are examined, it is possible to comment that the application is accepted and attracts attention because there are no participants who choose the option ' I would not be interested. I would not want to spend time on this application during my time at the airport.' There are some diverging answers when it comes to taking the time to participate. The main reason for this is that participants do not want physiological consequences such as sweating and fatigue. Additionally, the amount of discount coupons valid for food and beverage service providers and parking facilities was found to be low.

A significant majority evaluated the application as an innovative application that adds movement and fun to the journey process, which can be stressful and boring, and supports healthy living.

The participant coded as P3 stated that he encountered a similar practice at Bangkok Suvarnabhumi International Airport in 2013. He used bicycles there to try the application that interested him and added that he still keeps the T-shirt he earned as a result of pedaling as a souvenir. It contributed to one of the participants in the study being able to comment as someone who had experienced a similar application before.

The idea of using bicycles, which have a sustainability dimension and provide the energy needed in an environmentally friendly way, was supported by all participants. The answers given were shaped by the fact that the participants have been involved in the civil aviation sector for years, that they follow the current developments on climate, environment and sustainability, and that they have an awareness that all civil aviation stakeholders meet on a common denominator regarding sustainability.

When the findings of the second vignette were examined, it was seen that ' It would be an application that would interest me and support it. I would definitely take the time to participate' was preferred by all participants. The fact that the application of piezoelectric flooring in children's playgrounds in the terminal buildings was supported by every participant shows that the application is interesting and accepted. It is thought that this practice, which emphasizes sustainability, was approved by the participants because it supports the formation of awareness by aiming to raise awareness at an early age in the target audience.

P2 stated that the target audience will not only be limited to children, but also parents will be aware of the subject in the statement, "I think it will be a remarkable application for the child and raise awareness for their parents." From this perspective, it can be seen that it is not an application limited only to children, but has a wide impact area. Just as stated in the interviews about the first vignette, it has been a supported practice because it allows children and parents to have more fun before the journey, which can be stressful and boring, allows children to get rid of their excess energy, and this is reflected in their attitudes and behaviors in the cabin during the flight.

5. Conclusion

The trend towards non-conventional energy sources affects airports as well as all stakeholders in the civil aviation sector. Airports aim to use non-conventional energy sources such as solar, wind and biomass effectively. The manpower provided by their intense traffic formed the basis of this research. Electricity production from the human power energy in question; It has been examined under two subheadings: muscle power and electricity production with the piezoelectric principle.

There are many studies in the literature about electricity production by pedaling a bicycle within the scope of electricity production with muscle power. Electricity production studies with the piezoelectric principle are also frequently included in the literature. There are also examples of use in civil aviation and airport terminal buildings in studies and projects that reveal the areas of use of piezoelectricity in various modes of transportation.

In this research, scenarios of muscle power and piezoelectric principle, which are methods of electricity generation with human energy, that can be applied in airports are included. The opinions of aviation professionals on the relevant subject were received through the prepared vignettes. As a result of the content analysis, two separate themes belonging to two vignettes were obtained.

The theme of human movement-based energy production evaluation of possible muscle power applications suitable for in airport terminal consists of advantages and disadvantages categories. The advantages category consists of temporary categories such as attractive application and sustainable application, and the disadvantages category consists of temporary categories such as insufficient earnings, physical disadvantages and time constraints. Temporary categories, insufficient discount, more incentive, sweating, fatigue, insufficient time, interesting, rush to catch up, experienced, higher participation in domestic flights, an application that will give pleasure during the stressful journey, environmentally friendly, fun, healthy life, sustainability, tiring journey process and innovative application was found.

Although the first vignette, titled Electricity Generation by Pedaling a Bicycle, was described as meaningful and interesting by aviation professionals, it was evaluated as inadequate in terms of the incentives offered. Since the application requires physical effort, the feeling of fatigue and sweating it may cause have created hesitations against the application. In addition, it was concluded that it would not be possible for passengers who do not have enough time at the airport before their flight to participate in the application. On the other hand, the positive aspects of the application were determined by the participants as making a difference in terms of sustainability, having an environmentally friendly and innovative vision, supporting healthy living, and making waiting time fun.

The theme of human movement-based energy production evaluation of possible piezoelectric principle applications suitable for in airport terminal.

The advantages category consists of attractive application, calming down, awareness, increased business image, effective application, sustainable application, various gains, and the disadvantages category consists of time limitation. Temporary categories, sufficient time requirement, provided hygiene, attractive, interesting, the child's energy release, the child's calmness during the flight, remarkable, awareness raising, parental awareness, positive perspective towards the airport, an effective application on children, stressful travel process, for the child more stressful travel process, physiological imbalance and restlessness, a pleasant practice, comfortable and relaxing, sustainability, intercultural interaction, effective purpose, awareness formation, versatility was found.

In the second vignette, titled Piezoelectric Flooring Application in Children's Playgrounds in Terminal Buildings, all aviation professionals interviewed said, "It would be an application that would interest me and support it. I would definitely take the time to participate." It was stated that the areas cannot be used effectively if passengers have a time limit before the flight at the airport, and the necessity of ensuring hygiene conditions as a result of international activity in the playground was emphasized. It has been a supported practice, especially for children, as it makes the stressful part of the journey fun, allows them to relieve excess energy, and raises awareness about sustainability and environmentally friendly energy production. It has been a supported practice, especially for children, as it makes the stressful part of the journey fun, allows them to relieve excess energy, and raises awareness about sustainability and environmentally friendly energy production.

All these evaluations were made as a result of the experiences and opinions of professionals in the civil aviation sector. Their knowledge and awareness about sustainability, which is an important concept today, and their good knowledge of terminal operations and passenger profiles played a role in their presentation of relevant opinions.

The expected outputs of the research are that postmodern energy production applications based on human energy have a positive impact on the image of the airport and attract attention in the global showcase.

As a result of the findings obtained, it is thought that human movement-based post-modern energy production methods that can be implemented in airport terminals will form the basis for future research and operations.

In future studies, vignettes can be directed to different groups, taking into account the generation gap, and interviews can be held with children who are old enough to use playgrounds, accompanied by their parents. As a result, different results may be obtained from the research.

Ethical approval

An ethics committee application was made for the research on 13.04.2023, numbered E-60850919-300-2300020021. The ethics committee application numbered E-87914409-050.03.04-2300025331 was examined by the Social and Human Sciences Scientific Research and Publication Ethics Committee on 16.05.2023. The research was found ethically appropriate.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Performance Evaluation in Airline Operations Using SD and DNMA Methods Within The Framework of Sustainability: The Case of Turkish Airlines

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Abstract

Sustainability is essential in enabling enterprises to secure a competitive advantage and achieve long-term success. The sustainability activities of airline operations stand out in the evaluation of their performance alongside all other operational activities. Therefore, understanding how sustainability strategies affect performance in airline operations is a matter of significant concern for managers. This study aims to evaluate the performance of airline companies, particularly focusing on sustainability, using the example of Turkish Airlines (THY). In this study, the SD and DNMA methods, which are multi-criteria decision-making methods, were employed for performance evaluation. The weights of the criteria were determined using the SD method, and THY's performance between 2018 and 2022 was evaluated using the DNMA method. According to the analysis results, the three most important criteria are 'Sustainability Rating,' 'Load Factor,' and 'Number of Passengers,' with 2022 identified as the most successful performance year for THY. This study contributes to the literature by integrating sustainability performance in airline operations with both financial and non-financial indicators and by utilizing the SD and DNMA methods in an integrated manner. It is believed that the study provides significant contributions to the evaluation of sustainability practices' performance and can guide future sustainable strategies for THY and airline company managers.

1. Introduction

Sustainability, as defined by Porter and Kramer (2006), Glasby (2002), and Çakar (2007), encompasses meeting present needs without jeopardizing the ability of future generations to meet their own needs, living in harmony with the environment, and ensuring efficient utilization of resources for the social, economic, and environmental needs of future generations.

The three dimensions of sustainability—economic, social, and environmental—are examined within a holistic approach, emphasizing the importance of balancing these components in corporate governance (Dyllick and Hockerts, 2002). When businesses focused on economic interests contemplate their obligations to protect the environment for future generations and address social responsibilities, it becomes imperative to evaluate these dimensions together.

Social Sustainability deals with abstract issues such as education, employment, and ethics, and it pertains to preserving societal values. Basic needs of society such as food, clothing, and shelter are integral to social sustainability. The sustainability of social values and needs is also seen as a crucial step in determining the quality of economic sustainability (Eryılmaz et al., 2019).

Economic Sustainability is defined as preserving and preventing the degradation of capital (Goodland, 2002). At the heart of economic sustainability, which aims to plan the resources needed by future generations from today, lies the question of how each generation will decide how much capital to consume now and how much to accumulate and preserve for future generations (Markulev and Long, 2013, as cited in Bilgili, 2017). At a micro level, it focuses on the effective management of organizations' capital, requiring an optimal balance among various types of capital, including financial capital, tangible assets such as machinery and stocks, and intangible assets such as corporate reputation and technical knowledge.

Environmental Sustainability involves meeting the present and future generations' resource needs without compromising ecosystem health, considering the capacity limits of ecosystems, and ensuring their continued reproduction while meeting society's needs. Actions in environmental sustainability focus on resource conservation, waste management, and renewable energy systems, but true environmental sustainability can only be achieved through sustainable production and consumption practices (Goodland, 1995; Morelli, 2011).

The aviation sector is an integral part of the global economy but also poses challenges to environmental sustainability. It is one of the fastest-growing industries, paralleled by pollution that threatens environmental sustainability. Policymakers, researchers, and industry experts are addressing how to tackle these issues and achieve truly sustainable aviation, balancing the economic and other benefits it brings without pollution, noise, and loss of rural areas (Upham et al., 2012).

The sector's rapid growth, coupled with factors such as increased fuel consumption with the growing number of aircraft, international political disputes, etc., also increases airline costs, making sustainability increasingly important for aviation organizations from all perspectives. The sector has been at the forefront of sustainability efforts since the 1970s, presenting examples such as reducing aircraft engine noise levels, reducing fuel consumption, and using electronic resources and applications to prevent paper waste in ticketing processes and maintenance documents. Efforts to find solutions to problems such as aircraft routes, waiting times, time lost at airports, and inadequate traffic controls also continue (Torum and Yılmaz, 2019).

Sustainability in the aviation sector encompasses a comprehensive range of areas due to the size of stakeholders, including aircraft bodies and propulsion, auxiliary power systems, non-aircraft vehicles, fuel efficiency, airlines, airports, and air traffic control systems. While airlines and airports reflect their sustainability strategies in activity reports or provide separate sustainability reporting among all sector stakeholders, the number of reports is observed to be quite low.

The sustainability activities of airline operations are a significant factor in evaluating their performance, along with all other operational activities. Performance, viewed in the broadest sense as the degree of achievement of defined objectives, involves airlines utilizing various indicators based on predetermined goals in their performance analysis. Table 1 summarizes some of the key indicators used in performance analysis in airline operations (Leidtka, 2002: 111).

Table 1. Performance Measurement Indicators in Airline Operations

Category	Measure
FPMs – Financial Performance Measures	
Return on Investment	Return on Assets (F1A), Return on Equity (F1B), Return on Sales (F1C)
Financial Leverage	Debt to Assets (F2A), Debt to Equity (F2B), Long-term Debt/Assets (F2C)
Short-term Liquidity	Current Ratio (F3A), Quick Ratio (F3B)
Cash Position	Cash/Assets (F4A), Cash/Current Liabilities (F4B), Cash/Sales (F4C)
Capital Turnover	Sales/Assets (F5A), Sales/Equity (F5B), Sales/ (Long-term Debt+Equity) (F5C)
Receivables Turnover	Receivables Turnover (F6)
Cash Flow	CFFO/Assets (F7A), CFFO/Equity (F7B), CFFO/Sales (F7C)
NFPMs – Non-Financial Performance Measures	
Service Quality	On-time Flight Percentage (N1A), Percentage of Regularly Scheduled Flights Late 70% of the Time (N1B), Mishandled Baggage Reports per 1,000 Passengers (N1C), Involuntary Denied Boardings per 10,000 Passengers
Passenger Safety	Accidents and Incidents per Flight Hour (N2A), per Mile Flown (N2B), per Departure (N2C)
Customer Satisfaction	Consumer Complaints per 100,000 Passengers (N3)
Labor Efficiency	Available Seat Miles per Employee (N4A), Aircraft Miles per Employee (N4B), Departures per Employee (N4C)
Fixed Asset Efficiency	Passenger Load Factor (N5A), Airborne Hours per Plane (N5B), Aircraft Miles per Plane (N5C)
Materials Efficiency	Available Seat Miles per Gallon of Fuel (N6A), Aircraft Miles per Gallon of Fuel (N6B), Departures per Gallon of Fuel (N6C)
Passenger Volume	Percentage of Major Airline Revenue Seat Miles (N7A), Percentage of Major Airline Passengers (N7B)

Leidtka (2002) classified the performance indicators used in the measurement of airline companies' performance under two main categories. Financial Performance Metrics (FPMs) include criteria aimed at evaluating the company's financial condition, profitability, and financial sustainability, while Non-Financial Performance Metrics (NFPMs) consist of factors that assess the company's operational success and customer-focused processes, such as operational efficiency, customer satisfaction, service quality, and workforce productivity.

In the literature, it is recognized that relying solely on financial criteria or solely operational criteria is often insufficient for determining the performance of airline operations. Neglecting comprehensive and significant indicators such as sustainability activities results in the inability to evaluate the business from a broad perspective in performance assessment.

The aim of this study is to evaluate the sustainability-oriented performance of airline companies by integrating both financial and non-financial indicators. This study, which uses the SD and DNMA methods in an integrated manner from multi-criteria decision-making approaches, contributes to the literature by filling the existing gap in airline performance evaluation research.

Firstly, relevant studies in the literature were reviewed, followed by an explanation of the methodology used in the study. The application findings were presented, and the results obtained were discussed.

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2. Materials and Methods

In the literature, it is observed that different criteria are considered in measuring the performance of airline operations, with very few studies incorporating sustainability performance. Table 2 presents basic examples from these studies, as well as examples from other studies where Multi-Criteria Decision-Making Methods such as SD and DNMA are used for performance measurement. It is also noted that there are studies focusing on the relationship between sustainability scores and performance in sectors other than the aviation industry (Sinha et al., 2022; Kalia and Aggarval, 2022; Trisnowati et al., 2022; Xie et al., 2019; Velte, 2017; Brammer et al., 2006).

Table 2. Literature Review

The author/authors of the study	The subject/topic of the study.	Methodology.
Examples of Studies Evaluating the Performance of Airline Operations.		
Schefczyk, (1993)	Measurement of the Operational Performance of Airline Operations	Data Envelopment Analysis
Scheraga, (2004)	Measuring the Efficiency of Airline Operations	Data Envelopment Analysis and Tobit Regression Model
Kiracı and Bakır, (2018)	Examining the Performance of Airline Operations Before and After the Global Financial Crisis	CRITIC and EDAS
Tsai et al. (2011)	Evaluating the E-Marketing and E-Service Performance of Airlines in Taiwan	DEMATEL, ANP and VIKOR
Aydoğan (2011)	Measurement of the Performance of Turkish Aviation Companies	Rough Set-AHP and Fuzzy TOPSIS
Badi and Abdulshaded(2019)	Evaluating the Performance of Airline Operations in Libya	AHP and FUCOM
Özdağoğlu et al. (2020)	Evaluating the Performance of Airlines Operating at Isparta Süleyman Demirel Airport	BWM, MAIRCA and MABAC
Ustaömer et al. (2021)	Evaluating and Comparing the Efficiency of Turkish Airlines Before and After the Pandemic	Data Envelopment Analysis
Keleş, (2022)	Measurement of Turkish Airlines' Performance Over the Years	CRITIC and MABAC
Wang (2008)	Evaluating the Financial Performance of Taiwanese Airlines	Grey Relational Analysis, Fuzzy TOPSIS
Ömürbek and Kınay (2013)	Measurement of the Financial Performance of Airlines Listed on the Istanbul and Frankfurt Stock Exchanges	TOPSIS
Wanke et al. (2015)	Evaluating the Performance of Airlines Operating in Asia	TOPSIS/Markov Chain Monte Carlo Method
Barros and Wanke (2015)	Evaluating the Efficiency of African Airlines	TOPSIS, Neural Networks, DEAP
Akgün and Soy Temür (2016)	Pegasus and Türk Hava Yolları Companies' Financial Performance Measurement	TOPSIS
Asker, (2018)	Analysis of Efficiency in Traditional Airline Operations	Data Envelopment Analysis
Avcı and Çınaroğlu (2018)	Evaluation of Financial Performance of Airlines Operating in Europe	AHP-Based TOPSIS
Trabzon, (2022).	Financial Performance Measurement of Airlines Listed on Borsa Istanbul (BIST)	TOPSIS
Öncü et al. (2013)	Measurement of Financial Efficiency of Airlines Operating in	Data Envelopment Analysis
Asker, (2021)	Comparison of Financial and Operational Efficiency of Low-Cost Airlines	Data Envelopment Analysis
Heydari et al. (2020)	Assessment of Financial and Operational Performance of Airlines Operating in Iran	Data Envelopment Analysis
Macit and Göçer, (2020)	Measurement of Financial Performance of Airlines Listed on Borsa Istanbul (BIST)	Grey Relational Analysis (GRA)
Soltanzadeh Omrani (2018)	Evaluation of Performance of Airlines Operating in Iran	Data Envelopment Analysis

Studies on Performance Evaluation of Airline Operations: Research Examining Sustainability Performance		
Abdi et al. (2020)	The Impact of Sustainability on Firm Value and Financial Performance in Airline Operations	Panel Data Analysis
Sisman et al. (2020)	The Impact of ESG Data on Financial Performance in Airline Operations	Panel Data Analysis
Abdi et al. (2021)	The Impact of ESG Data on Firm Value and Financial Performance in Airline Operations	Panel Data Analysis
Ay et al. (2023)	The Effect of Sustainability Performance on the Financial Performance of Airline Companies During the COVID-19	Panel Data Analysis
Kiracı et al. (2022)	Analysis of Factors Influencing the Sustainable Success of Airline Companies During the COVID-19 Pandemic	IT2FAHP IT2FDEMATEL
Kiracı (2022)	Sustainability and Financial Performance: A Study of the Airline Sector	Data Envelopment Analysis
Examples of Studies Applying Multi-Criteria Decision-Making Methods such as SD and DNMA		
Liao et al. (2019)	Evaluation of Lung Cancer Screening Process	DNMA
Nie et al. (2019)	Location Selection for Shopping Mall	DNMA
Lai et al. (2020)	Selection of Cloud Service Providers	DNMA
Saha et al. (2022)	Selection of Waste Treatment Method	DNMA
Ecer et al. (2022)	Assessment of Economic Freedom: The Case of OPEC Countries	DNMA
Hezam et al. (2022)	Assessment of Alternative Fuel Vehicles from a Sustainability Perspective	DNMA
Ünal (2019)	Measurement of Financial Success of Private Equity Commercial	SD, WASPAS
Bağcı and Yiğiter (2019)	Financial Performance Analysis of Companies Operating in the Energy Sector	SD, WASPAS
Aydın (2020)	Financial Measurement of Foreign Deposit Banks	SD, COPRAS
Işık (2020)	Evaluation of Financial Performance of Development and Investment Bank	SD, MABAC, WASPAS
Koşaroğlu (2020)	Financial Analysis of Banks	SD, EDAS
Demir (2022)	Performance Analysis of Anadolu Insurance Company Over the Years	SD, PSI, BAYES, MABAC
Karaköy et al. (2023)	Analysis of Economic Freedom Indexes of Former Soviet Union Countries	SD, CoCoSo
Pala (2023)	Performance Analysis in the Food Sector	SD, WISP

In the literature, it is observed that different criteria are considered in measuring the performance of airline operations, with very few studies incorporating sustainability performance. Table 2 presents basic examples from these studies, as well as examples from other studies where Multi-Criteria Decision-Making Methods such as SD and DNMA are used for performance measurement. It is also noted that there are studies focusing on the relationship between sustainability scores and performance in sectors other than the aviation industry (Sinha et al., 2022; Kalia and Aggarval, 2022; Trisnowati et al., 2022; Xie et al., 2019; Velte, 2017; Brammer et al., 2006).

In the literature review focusing on studies on the performance of airline operations, no study was found that examines both sustainability performance and financial/non-financial indicators together. Additionally, there is no study found that utilizes SD and DNMA methods together for measuring sustainability and performance in airline operations. Given that a few studies within the aviation sector focusing on sustainability mainly concentrate on financial performance and often prefer panel data analysis as the research method, it is evaluated that this study will contribute to filling the gap in the literature.

3. Metodology

In this study, the SD and DNMA methods, which are current multi-criteria decision-making techniques, have been utilized.

SD (Standard Deviation) and DNMA (Double Normalization-based Multiple Aggregation) methods are commonly used contemporary techniques within multi-criteria decision-making (MCDM) approaches. The SD method is an effective technique for determining the weight of criteria based on the standard deviation approach, calculating the variability and importance of each criterion (Pala, 2023). The DNMA method is a flexible and reliable decision-making technique that combines linear and vector normalization techniques to rank alternatives in a way that they are closest to the expected value (Wu and Liao, 2019). While SD helps in understanding the dynamic relationships between indicators,
DNMA provides a comprehensive ranking mechanism by integrating multiple criteria.
In this study, the combined use of SD and DNMA methods ensures that the weights of the criteria are determined objectively and provides more reliable results during the performance evaluation process. Literature shows that the DNMA method has been applied in various fields such as healthcare (Liao et al., 2019), shopping mall location selection (Nie et al., 2019), and sustainable fuel vehicle assessment (Hezam et al., 2022). However, as there is no study in the literature, especially in the aviation sector, that uses both SD and DNMA methods together, this study is considered to make a significant contribution to the literature.

3.1. SD (Standard Deviation) method

SD process is in Table 2 (Pala, 2023, 67).

i:alternative;i=1,2,3,…,m

j:criterion;j=1,2,3,…,n

x_ij:performance value

h_ij:normalized value first step

t_ij:normalized value

(t_j)̅:average

σ_j:standard deviation

w_j:weigh

Table 3. SD method

Step	Equation	Equation no
Decision matrix	$D=\begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix}$	(1)
Normalization first step	$h_{ij}=\left[\frac{x_{ij}-\min_j x_{ij}}{\max_j x_{ij}-\min_j x_{ij}}\right]$	(2)
Normalization benefit criterion	$t_{ij}=h_{ij}$	(3)
Normalization cost criterion	$t_{ij}=-h_{ij}+\max_j h_{ij}+\min_j h_{ij}$	(4)
Standard deviation	$\sigma_j=\sqrt{\frac{\sum_{i=1}^{m}(t_{ij}-\bar{t_j})^2}{m}}$	(5)
Weight	$w_j=\frac{\sigma_j}{\sum_{j=1}^{n}\sigma_j}$	(6)

3.2. DNMA (Double Normalization-based multiple Aggregation) method

DNMA process is in Table 3 (Özçil, 2020, 59-61).

$i: alternative; i = 1,2,3,\dots,m$

$j: criterion; j = 1,2,3,\dots,n$

$x_{ij}: performance\ value$

$x_{ij}^1: linear\ normalization$

$x_{ij}^2: vector\ normalization$

$u_1(a_i): total\ weighted\ lienar\ normalization$

$r_1(a_i): first\ type\ rank$

$u_2(a_i): second\ integration\ function\ for\ linear\ normalization$

$r_2(a_i): second\ type\ rank\ (ascending\ order)$

$u_3(a_i): third\ integration\ function$

$r_3(a_i): third\ type\ rank$

$u_1^N(a_i): first\ normalized\ integration\ function$

$u_2^N(a_i): second\ normalized\ integration\ function$

$u_3^N(a_i): third\ normalized\ integration\ function$

Table 4. DNMA process

Step	Equation	Equation no
Linear normalization (benefit criterion)	$x_{ij}^1=1-\left\|\frac{x_{ij}-\max_j x_{ij}}{\max_j x_{ij}-\min_j x_{ij}}\right\|$	(7)
Linear normalization (cost criterion)	$x_{ij}^1=1-\left\|\frac{x_{ij}-\min_j x_{ij}}{\max_j x_{ij}-\min_j x_{ij}}\right\|$	(8)
Vector normalization (benefit criterion)	$x_{ij}^2=1-\frac{\left\|x_{ij}-\max_j x_{ij}\right\|}{\sqrt{\sum_{i=1}^{m}(x_{ij})^2+\left(\max_j x_{ij}\right)^2}}$	(9)
Vector normalization (cost criterion)	$x_{ij}^2=1-\frac{\left\|x_{ij}-\min_j x_{ij}\right\|}{\sqrt{\sum_{i=1}^{m}(x_{ij})^2+\left(\min_j x_{ij}\right)^2}}$	(10)
Total weighted linear normalization	$u_1(a_i)=\sum_{j=1}^{n}[w_j x_{ij}^1]$	(11)
Second integration function for linear normalization	$u_2(a_i)=\max_j[w_j(1-x_{ij}^1)]$	(12)
Second integration function (vector normalization)	$u_3(a_i)=\prod_{j=1}^{n}[x_{ij}^{2\,w_j}]$	(13)
The first normalized integration function	$u_1^N(a_i)=\frac{u_1(a_i)}{\sqrt{\sum_{i=1}^{m}[u_1(a_i)]^2}}$	(14)

The second normalized integration function

$$u_2^N(a_i) = \frac{u_2(a_i)}{\sqrt{\sum_{i=1}^{m}[u_2(a_i)]^2}} \quad (15)$$

The third normalized integration function

$$u_3^N(a_i) = \frac{u_3(a_i)}{\sqrt{\sum_{i=1}^{m}[u_3(a_i)]^2}} \quad (16)$$

Final value

$$S_i = \sqrt{\varphi[u_1^N(a_i)]^2 + (1-\varphi)\left[\frac{m - r_1(a_i) + 1}{\frac{m(m+1)}{2}}\right]^2} - \sqrt{\varphi[u_2^N(a_i)]^2 + (1-\varphi)\left[\frac{r_2(a_i)}{\frac{m(m+1)}{2}}\right]^2} + \sqrt{\varphi[u_3^N(a_i)]^2 + (1-\varphi)\left[\frac{m - r_3(a_i) + 1}{\frac{m(m+1)}{2}}\right]^2} \quad (17)$$

4. Application

In the study, the most commonly used financial and non-financial performance indicators in the literature for measuring the performance of airline companies have been employed as criteria. The descriptions and measurement units of these criteria are provided in Table 5. All criteria are benefit-oriented.

Decision matrix is in Table 6. The scores for THY (Turkish Airlines) for the criteria between 2018 and 2022 are presented in Table 5. The study evaluates Turkish Airlines' (THY) performance between 2018 and 2022. In the sustainability reporting of airlines, using different criteria in different periods makes it difficult to monitor performance (Kasa, Göçmen, & Sümer, 2025). To address this issue, global reporting frameworks have been established to standardize the criteria for publishing sustainability reports. Among these, the Global Reporting Initiative (GRI) Standards Series, prepared in 2016 and implemented in 2018, is the most widely preferred and used framework (Güney & Dinler, 2021). The GRI Standards adopted by THY ensure more consistent and comparable sustainability reporting in the airline industry, facilitating performance monitoring. Another key reason for selecting this period is that it covers the pre-pandemic, pandemic, and recovery phases, offering a comprehensive analysis of the changes in the aviation sector. Evaluating a longer period would require considering the impact of different economic and sectoral dynamics. Furthermore, since 2022 marks the recovery period for Turkish Airlines, the strategic decisions taken during this time and their impacts can be observed more clearly, supporting the study with up-to-date findings. Future studies analyzing longer periods could provide a broader understanding of the general trends in the industry

Table 5. Description of Criteria

Criterion		Description	Unit of Measurement
K1	Available Seat Kilometers	Total number of seats sold multiplied by the distances of flight legs	Seat*Km
K2	Sustainability Rating	Rating of the airline's environmental, social, and governance sustainability activities (SandP Global Consulting)	Score
K3	Number of Passengers	Number of traveling passengers	Quantity
K4	Cargo Mail Tons	Total air cargo carried for the relevant year	Tons
K5	Load Factor	Ratio of revenue passenger kilometers (passenger * km) to offered seat kilometers	Percentage ratio
K6	Destination Served	Flight points on a city-by-city basis	Quantity
K7	Number of Aircraft	Number of aircraft owned or leased by the airline company	Quantity
K8	Earnings Per Share	Ratio of net profit to outstanding shares of the airline company	USA (Sent)
K9	Number of Employees	Total number of employees in the airline company	Quantity
K10	Net Income/Loss for the Period	Net profit or loss for the company for the relevant year	Million Dollars (USD)
K11	Revenue Passenger Kilometers	Total revenue generated by multiplying the distances of flight legs by the number of seats sold	Km*Seat
K12	Labor Productivity	Ratio of offered seat kilometers to the total number of personnel	Percentage ratio
K13	Flight Hours	Average daily flight hours per passenger aircraft	Hour

The performance measurement criteria (K1-K13) used in this study were determined by considering commonly used financial and operational indicators as well as sustainability-focused criteria for evaluating the performance of airline companies (Asker, 2018; THY, 2022 Annual Report). In addition to frequently used indicators in the airline industry, such as Available Seat Kilometers (K1), Load Factor (K5), and Number of Passengers (K3), next-generation criteria like Sustainability Rating (K2) were also included to measure sustainability performance (Abdi et al., 2021; Sisman et al., 2020).

The selected criteria were obtained from Turkish Airlines' annual reports for the 2018-2022 period (THY, 2022) and are commonly used in the performance evaluation of other airlines in the industry. The necessity for defining new criteria in performance measurement depends on the company's strategic objectives and developments in the sector. For instance, environmental sustainability-focused criteria such as carbon footprint and the percentage of renewable energy usage could be incorporated into performance evaluations in the future

Table 6. Decision matrix

Years	2018	2019	2020	2021	2022
K1	182.030.829	187.717.317	74.960.299	127.768.987	201.734.516
K2	21	20	44	47	51
K3	75.167.807	74.282.218	27.950.200	44.787.730	71.817.525
K4	1.413.401	1.544.342	1.487.233	1.879.552	1.678.953
K5	81.9	81.6	71	67.9	80.6
K6	310	321	324	333	337
K7	332	350	363	370	394
K8	0.55	0.57	-0.61	0.69	1.97
K9	149.131.349	153.202.555	53.249.000	86.701.053	162.665.250
K10	68.0769	63.6524	26.1477	46.4074	68.3383
K11	12:16	12:40	06:28	08:19	10:50

In the study, the weights of the criteria were first determined using the SD method. The scores for the normalization process, which is the first step of the SD method, are provided in Table 7. Standard deviation and weights are in Table 8.

Table 7. Normalization (SD)

t_{ij}	2018	2019	2020	2021	2022
K1	0.8446	0.8894	0.0000	0.4166	1.0000
K2	0.0323	0.0000	0.7742	0.8710	1.0000
K3	1.0000	0.9812	0.0000	0.3566	0.9290
K4	0.0000	0.2809	0.1584	1.0000	0.5697
K5	1.0000	0.9786	0.2214	0.0000	0.9071
K6	0.0000	0.4074	0.5185	0.8519	1.0000
K7	0.0000	0.2903	0.5000	0.6129	1.0000
K8	0.4496	0.4574	0.0000	0.5039	1.0000
K9	0.8763	0.9135	0.0000	0.3057	1.0000
K10	0.9938	0.8889	0.0000	0.4802	1.0000
K11	0.9355	1.0000	0.0000	0.2984	0.7043

Table 8. σ_j, w_j values

	σ_j	w_j
K1	0.3722	0.0897
K2	0.4302	0.1037
K3	0.4046	0.0975
K4	0.3525	0.0850
K5	0.4240	0.1022
K6	0.3514	0.0847
K7	0.3331	0.0803
K8	0.3171	0.0764
K9	0.3948	0.0952
K10	0.3864	0.0931
K11	0.3830	0.0923

When evaluating the weights of the criteria, it is observed that Turkish Airlines' sustainability rating criterion (K2) stands out among all criteria (with a wj value of 0.1037). The load factor criterion (K5), which is widely used in the literature as an important measure reflecting the commercial success and operational efficiency of airline companies, follows closely behind the sustainability rating criterion with a wj value of 0.1022. High load factors are associated with more effective flight planning, increased profitability, and economic sustainability. Moreover, aircraft that are fuller and managed with accurate capacity reduce waste generation and carbon emissions, thus being linked to environmental sustainability as well. Overall, when evaluating the weights of the criteria, it is seen that Turkish Airlines' sustainability performance stands out among all criteria, and it is as important as the load factor criterion, which is commonly used in measuring the performance of airline operations. Additionally, Turkish Airlines' performance between 2018 and 2022 has been evaluated using the DNMA method. DNMA linear normalization results are in Table 9.

Table 9. x_{ij}^{1} values

	2018	2019	2020	2021	2022
K1	0.8446	0.8894	0.0000	0.4166	1.0000
K2	0.0323	0.0000	0.7742	0.8710	1.0000
K3	1.0000	0.9812	0.0000	0.3566	0.9290
K4	0.0000	0.2809	0.1584	1.0000	0.5697
K5	1.0000	0.9786	0.2214	0.0000	0.9071
K6	0.0000	0.4074	0.5185	0.8519	1.0000
K7	0.0000	0.2903	0.5000	0.6129	1.0000
K8	0.4496	0.4574	0.0000	0.5039	1.0000
K9	0.8763	0.9135	0.0000	0.3057	1.0000
K10	0.9938	0.8889	0.0000	0.4802	1.0000
K11	0.9355	1.0000	0.0000	0.2984	0.7043

Table 10. x_{ij}^{2} values

	2018	2019	2020	2021	2022
K1	0.9525	0.9662	0.6941	0.8215	1.0000
K2	0.7028	0.6929	0.9306	0.9604	1.0000
K3	1.0000	0.9944	0.6999	0.8069	0.9787
K4	0.8852	0.9174	0.9034	1.0000	0.9506
K5	1.0000	0.9984	0.9427	0.9264	0.9932
K6	0.9663	0.9800	0.9838	0.9950	1.0000
K7	0.9312	0.9512	0.9656	0.9734	1.0000
K8	0.5328	0.5394	0.1511	0.5789	1.0000
K9	0.9590	0.9713	0.6686	0.7699	1.0000
K10	0.9982	0.9676	0.7079	0.8482	1.0000
K11	0.9849	1.0000	0.7656	0.8356	0.9307

$u_1(a_i), u_2(a_i), u_3(a_i)$ are in Table 10.

When considering all the performance criteria addressed in the study, as stated in Table 13, the year 2022 stands out as Turkish Airlines' most successful year between 2018 and 2022.

The year 2022 marked the beginning of the aviation sector's recovery from the impacts of the COVID-19 pandemic. Turkish Airlines emerged as one of the airlines that benefited most from this recovery by responding swiftly and effectively to the increasing travel demand and continuing to invest in human resources, in contrast to other airlines (THY, 2022 Annual Report).

Table 11. $u_1(a_i), u_2(a_i), u_3(a_i)$ values

	$u_1(a_i)$	$u_2(a_i)$	$u_3(a_i)$
2018	0.5754	0.1003	0.8926
2019	0.6541	0.1037	0.8977
2020	0.2004	0.0975	0.7165
2021	0.5086	0.1022	0.8592
2022	0.9197	0.0366	0.9864

$u_1^N(a_i), u_2^N(a_i), u_3^N(a_i)$ are in Table 11.

Table 12. $u_1^N(a_i), u_2^N(a_i), u_3^N(a_i)$ values

	$u_1^N(a_i)$	$u_2^N(a_i)$	$u_3^N(a_i)$
2018	0.4171	0.4890	0.4563
2019	0.4741	0.5053	0.4589
2020	0.1452	0.4753	0.3662
2021	0.3686	0.4980	0.4392
2022	0.6666	0.1782	0.5042

Table 13. Final Values and Ranks

	S_i	Rank
2018	0.3058	3
2019	0.3319	2
2020	0.0272	5
2021	0.2023	4
2022	0.8199	1

Thanks to its extensive flight network, increased human resources, renewed fleet structure, dynamic capacity management, robust cargo operations, and sustainability efforts, Turkish Airlines maximized the benefits of the rising demand. In 2022, Turkish Airlines also received numerous awards for its sustainability performance (e.g., the "Bronze" award from Ecovadis in 2021 and the "Silver" award in 2022, recognition as the "Most Sustainable Flag Carrier Airline" by World Finance in 2022, and "Airline of the Year in Sustainability Innovation" by CAPA - Centre for Aviation in 2022, etc.) (THY, 2023).

According to the research findings, the year 2019 is considered the second most successful year for Turkish Airlines. Although it represents a positive period in terms of overall performance, it falls short compared to the performance in 2022.

For the examined periods, the years 2018 and 2021 are considered to be of moderate performance level. These years represent periods where the company demonstrated stable performance but did not reach its highest level of success.

Regarding the years 2018-2019, it is possible to say that increasing fuel prices, global economic uncertainties, and intensified competition were factors affecting performance in the aviation sector.

According to the research findings, the year 2020 marks the lowest performance. The year 2020 was the year when the COVID-19 pandemic most significantly impacted the aviation sector. Travel restrictions and quarantines led to a significant decrease in travel demand, and Turkish Airlines' passenger load factors also declined significantly. Towards the end of 2021, vaccination efforts accelerated worldwide, and travel restrictions were eased, leading to an increase in travel demand. This resulted in a surge in cargo transportation, which became a significant source of revenue for airlines during the early stages of the pandemic. Turkish Airlines benefited from this situation thanks to its strong cargo operations.

5. Conclusion

Sustainability holds critical importance in gaining a competitive advantage and ensuring long-term success in the airline sector. Airline companies can enhance their financial performance while fulfilling their environmental and social responsibilities by prioritizing sustainability at the core of their strategies and operations. Many airlines have begun developing and implementing sustainability-focused strategies and practices to reduce environmental impacts, use resources more efficiently, and fulfill social responsibilities.

The sustainability activities of airline operations are a significant factor in evaluating their performance, along with all other operational activities. However, it is observed that very few studies consider sustainability performance as a performance indicator for airline companies. Often, the focus is solely on financial criteria or solely on operational criteria, leading to the neglect of comprehensive and significant indicators such as sustainability activities and preventing the evaluation of the company from a broader perspective.

In this study, the performance of Turkish Airlines was evaluated within the framework of sustainability. The main objective of the study is to emphasize the importance of sustainability in the airline sector and analyze how this criterion affects the performance of airline companies. The research findings indicate that Turkish Airlines' sustainability practices are a significant factor in performance evaluation and stand out among other performance criteria. Particularly, it has been determined that sustainability performance should be considered alongside key performance indicators commonly used in the airline industry, such as the load factor.

Turkish Airlines' performance between 2018 and 2022 was evaluated on a yearly basis using eleven criteria. In the evaluation process, contemporary multi-criteria decision-making methods, including SD and DNMA, were integrated. The SD method was utilized to determine the weights of the criteria, while the DNMA method was employed to analyze Turkish Airlines' performance during the specified period.

In the evaluation of criterion weights using the SD method, the top three criteria with the highest weights were "Sustainability rating," "Load factor," and "Number of passengers," respectively. The criterion with the lowest weight was "Earnings per share." These results indicate that sustainability performance is a more meaningful indicator than traditional criteria in determining the performance of airline operations. Earnings per share is used to measure financial performance and generally reflects profitability over a specific period. It can be stated that sustainability and operational efficiency are more effective in evaluating long-term success compared to other criteria.

In the performance evaluation of Turkish Airlines (THY) between 2018 and 2022 using the DNMA method, it is observed that Turkish Airlines' performance varied over time, with the highest performance occurring in 2022. The analysis of Turkish Airlines' performance indicates significant improvement after the post-pandemic recovery period. The increase in personnel productivity and sustainability scores in 2022 highlights Turkish Airlines' emphasis on environmental and social responsibility and its alignment with sustainable practices in the industry. This comprehensive analysis fills the gap in the literature by integrating sustainability performance with financial and non-financial indicators, demonstrating how Turkish Airlines responded to industry challenges with flexibility and strategic adaptation.

Given the low performance in 2020, the need for strategic measures to mitigate weaknesses and enhance resilience during crises becomes evident. When faced with global crises like COVID-19, it is observed that companies with high sustainability performance tend to perform better, and their resilience is higher. (Aksoy, 2020; Abdi et al., 2020; Ay et al., 2023).

The study demonstrates that prioritizing sustainability in airline operations can enhance their long-term success and competitiveness. Additionally, it shows that integrated performance evaluation using multi-criteria decision-making methods such as SD and DNMA can provide valuable insights to airline company managers.

The study emphasizes the necessity of integrating sustainability into airline performance evaluation frameworks. Future research could discuss the impact of sustainability-focused investments and technological advancements on aviation performance. Since the study focuses on a single airline company, expanding the analysis to compare multiple airline companies could provide a more comprehensive understanding of sustainability's role in airline industry performance. Additionally, considering alternative criteria beyond what is presented in Turkish Airlines' reports could further enhance the comprehensiveness of sustainability assessments.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Air Transportation Security Measures: Ics2

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Abstract

In this research, ICS 2 security measures in airline transportation were examined. The aim of this research is to investigate security measures in airline transportation and the economic effects of the ICS 2 application which the EU has implemented in customs on air transportation. The EU Commission with its proposal for a new Customs Code (R-UCC) has proposed that the EU Customs Data Center is managed by the national EU Customs Authority that be given to the person declaring that the raw material, product or semi-processed product has been brought into the EU or removed from the EU. In this research, the effects of the ICS2 reform on the stakeholders of the supply chain, customs procedure were discussed and the reasons for the different treatment of some traders in ICS2 was examined. The research used quantitative research method. In France, Germany, Switzerland, Sweden where ICS 2 which started to be implemented in 2021 was implemented the application results in 2017, 2018, 2019 before ICS 2 implementation and 2022, 2023 and 2024 (10 months) after ICS 2 were examined in 2 periods. The conveniences brought by ICS 2 during the transportation of products with codes HS 07, HS 08, HS 30, HS 71 transported by air transportation mode were evaluated. JAMOVI 2.3.24, SPSS 24, PSPP programs were used in the research and the data were analyzed with ANOVA test. According to the research result, ICS2 significantly shortens the delivery time. It is thought that this research may be important for those who research the delivery times of ICS2 in the future.

1. Introduction

The European Union (EU), which has 27 members (Union E., 2024) that make up 6% of the world's population is the world's largest political, economic, and commercial community. With its large market structure and advanced infrastructure, it has a large structure managed by directives prepared by the European Parliament in many areas that are tried to be standardized in all member countries. The European Community Commission in 1961 has followed the policy of;

- Creating a free competition environment,
- Making infrastructure arrangements,
- Establishing a pricing system,
- Making taxation and related institutions financially

and commercially independent and autonomous. Ensuring the harmony of transportation markets that preventing monopolization. Creating logistics and employment areas in all transportation modes on border lines, contributing to economic and social life standards (Alperen, 2018). Various R&D studies (Marco Polo Program, Trans European Transport Networks etc.) with the aim of setting standards among international and EU members in order to increase efficiency in transportation in Europe. One of these studies is ICS 2. The transportation policy of the European Union is to increase energy efficiency to take necessary measures in the field of logistics regarding global climate change. A new one has been added to EU policies with the idea that ICS2 will save time, energy and manpower.

2. EU and International Trade

The EU is a union with a significant surface area of the world economy and trade and a political power that cannot be underestimated. The EU is the second largest economy in the world (after the USA) with a consumer capacity of 449.2 million (Bloomberg, 2024) and a per capita income of $ 33,928 and a Gross Domestic Product (GDP) of 9 trillion 949 billion 792 million TL in the second quarter of 2024 (Commission, 2024).
The Table 1 shows the import values of EU countries from world countries in 2019-2023. While import values were low due to Covid 19 that import values increased in 2022-2023.

Table 1. 2019-2023. The EU Countries -World Countries import export values

Product Code	Product Label	Imported Value In 2019, US Dollar Thousand	Imported Value In 2020, US Dollar Thousand	Imported Value In 2021, US Dollar Thousand	Imported Value In 2022, US Dollar Thousand	Imported Value In 2023, US Dollar Thousand
TOTAL	All Products	19.097.074.798	17.725.978.906	22.455.262.414	25.406.356.836	23.553.539.406
Product Code	Product Label	Exported Value In 2019, US Dollar Thousand	Exported Value In 2020, US Dollar Thousand	Exported Value In 2021, US Dollar Thousand	Exported Value In 2022, US Dollar Thousand	Exported Value In 2023, US Dollar Thousand
TOTAL	**All Products**	18.761.814.917	17.514.968.797	22.154.054.456	24.719.795.601	23.291.072.313

Search (www.trademap.com 12.10.2024).

It has an EU export rate of $ 7.2 trillion (Trade Map 2023) and an import rate of $ 7.0 billion (Trade Map 2023). It has a share of 15.2% in world goods exports; and a share of 14.7% in world imports. It ranks second in world goods exports and imports. It has a trade capacity of $ 112 billion in services trade (Council, 2024).

3. European Import Control System 2 (ICS2)

The EU Customs Union was established in 1968 to facilitate trade between EU companies and to equalize customs duties on goods coming from abroad. The EU considers all member states as one country. They apply the same tariffs to goods imported into their territory from the rest of the world and no tariffs at all. No customs duties are paid when goods are transported from one EU country to another.

The EU has developed policies to prevent smuggling. The EU's Rome Treaty and the EU Treaty (Maastricht Treaty, the second White Paper in 2001) forms the basis of transportation policies. According to these agreements, the adoption of common transportation policies among. EU member states and the codification of the legislation of all member states are taken as basis. EU transportation policies aim to promote global climate safe and clean transportation in European countries, liberalization of trade in the common market, safe import and export (Affairs, 2024).

In accordance with the transportation policy, ensuring the sustainability of transportation services, road safety, the sector's compliance with a safe, green economy, common, uniform, and mandatory practices have been put into effect with the adoption of new legislation and negative environmental impacts have been reduced.

The EU has introduced the ICS2 system for road, air, sea and postal operators, cargo transportation and crossings to one of the EU member states. This system is known as the electronic customs system of EU member states based on the principle that economic operators submit PLACI data before loading and ENS data before arrival, detailed cargo information and risk analyses to the EU Customs Administrations in order to ensure the security of EU member states (Taxation, 2024).

The EU's ICS2 application is one of the EU transportation policies and the White Paper's common transportation policies. The European Union affected by the COVID-19 pandemic that has amended its legislation to facilitate the implementation of an alternative and expedited process for EU aviation security and verification of supply chain operators of member countries. To this end, in the context of the International Civil Aviation Organization (ICAO) and the World Customs Organization (WCO), the WCO has promoted the development of the international policy concept of Pre-Loading Advance Cargo Information (PLACI) which is used to define a specific 7+1 data set (3), as defined in the SAFE Framework of Standards (SAFE FOS).

Air carriers and postal operators upload their shipment data to the system as soon as possible before and after the departure of the cargo and their documents at the point of departure. Article 186 of Commission Implementing Regulation (EU) 2015/2447 (5) determines the risk analysis and control process applied by the customs office of first entry and Article 182 of that Regulation establishes the Import Control System (ICS2) designed by mutual agreement between the Commission and the Member States which is essential for the submission of details of entry summary declarations which requests for modification, requests for invalidation, processing and storage and sharing of relevant information with the customs authorities (Commission, 2021).

Customs duties constitute around 14% of the total EU budget. Customs controls at the EU's external borders protect consumers from goods and products that may be dangerous or bad for their health. They protect animals and the environment by preventing endangered animal species, illegal trade, plant, and animal diseases. EU customs controls protect national governments against tax and duty fraud as well as against irregular tax evasion by companies and individuals (European-Union, 2024).

On May 1, 2016, the European Union (EU) initiated a study to digitalize the data transfer, storage and customs transactions of economic operators with the Union Customs Code (BGK).

Import Control System 2 (ICS2) has introduced the requirement that responsible operators going to or transiting to EU member states must report their summary declaration data to EU customs via ICS2 before they reach the EU member state. The first version of the system which is planned to be implemented in three versions that entered into force on March 15, 2021 for "air cargo transportation pre-loading" and "air mail transportation pre-loading" processes; and the second version entered into force on March 1, 2023 for "air general cargo transportation", "air transportation" and "mail transportation".

ICS 2 is implemented in three stages:

- Publication 1 15.03.2021 mail and courier (taxation-custom, 2021)
- Publication 2 01.03.2023 airline (Taxation, 2023)
- Publication 3 01.03.2024 land sea railway (Taxation-2024)

Since July 1, 2023, the system has been implemented in the airline.

Figure 1. ICS2 Timeline Search: IATA, 2024.

The third version is planned to be gradually implemented in maritime, rail and road transport on 3rd of June 2024 with maritime carriers expected to start on 3rd of June 2024 and no later than 4th of December 2024 and their interim filings (house level filing) on 4th of December 2024 and no later than 1st of April 2025 and rail and road carriers expected to start on 1st of April 2025 and no later than 1st of September 2025 (TIM, 2024). Version 3 to be processed by the European Commission on 1st of March 2024.

ICS2 is the EU's new advanced cargo information system supporting the implementation of the customs safety and security regulator Summary Declaration (ENS) which collects data from Economic Operators (EO) entering and transiting the EU prior to arrival in the EU. The program is one of the main contributors towards establishing an integrated EU approach to reinforce customs risk management under the common risk management framework (CRMF).

ICS2 / PLACI requests information such as the sender name, sender address (including postal code and telephone number), recipient name, recipient address (including postal code and telephone number), number of pieces. Gross weight, detailed goods description, if any, HAWB number. In the global economy, it aims to increase the security measures of goods entering the EU customs area, ensuring the security and efficiency of international trade and to facilitate customs procedures. Threats are detected by subjecting them to safety and security risk analysis within the scope of the EU Common Risk Management Framework. The EU Common Risk Management Framework states that when a summary declaration is submitted for a vehicle and goods entering any EU member country that have common risk criteria are applied within the scope of the EU common risk analysis system.

We can list the risks within the scope of safety and security as explosives, narcotics, precursors, dangerous counterfeit drugs, dangerous toys or electronics, contaminated foods, weapons and all kinds of organized smuggling in air cargo (TAXUD/2022/OP/0001). Although the word "import" is included in the name of the system that the system doesn't cover a control related to the free circulation entry regime (TAXUD, 2022). ICS ensures that import transactions started in a member country can be completed in another member country without re-submitting the entry summary declaration (ENS). The ENS then enters the risk assessment and the safety also security data is transmitted to the other member state. (Revenue, 2024). After the carrier submits a summary declaration to a country customs administration integrated into the system and this information is also transmitted to the customs administrations of the other countries where the vehicle will stop and thus eliminating the need to submit a summary declaration again to the other country customs administrations integrated into the system.

With PLACI (Pre-Loading Advance Cargo Information) / ICS2 application, detailed information about cargoes going to European Union countries and planned to be transit-transferred must be sent to the relevant authorities of the first country of arrival by the transport business organizer or the airline before the cargo is loaded onto the plane (BULTEN, 2024).

The entry of goods into the EU consists of a 5-stage process. ICS2 covers the first three of these stages. (TAXUD, 2022)

1) Submission of the entry summary declaration (ENS) (within the scope of ICS2)

2) Notification of arrival of the means of transport (within the scope of ICS2)

3) Presentation of goods to customs (within the scope of ICS2)

4) Temporary storage of goods

5) Subjecting the goods to a customs regime

It is stated that the postal operators inside and outside express, air cargo carriers, consigner established in the EU.

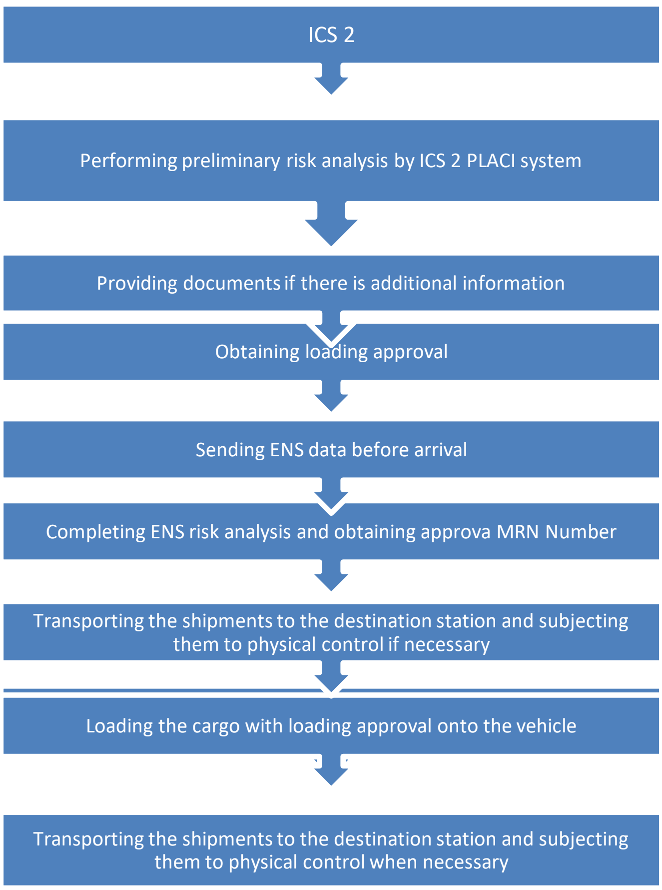

Figure 2. ICS 2 transaction steps Search (Comission, Taxation, 2024)

3 .1. Advantages of ICS 2

The main reason for the introduction of ICS 2 is to ensure the safety and security of the citizens of the Union member states and the EU common market. Every year, goods worth a trillion

Euros enter the EU and 15% of world goods trade passes through the EU. For this reason, the EU implements a safety and security program before the arrival of goods to ensure the safety of its citizens and market. (TAXUD, 2022)

The European Union Import Control System 2 (ICS2) requires detailed electronic advance arrival declarations (PLACI Pre Loading Advance Cargo Information) to be made for goods entering the customs area to strengthen the security measures of the imported product or service to facilitate customs procedures to protect borders and to increase efficiency and productivity in trade. The declaration requests information that will enable advanced risk assessments by importers, carriers or their representatives and customs authorities.

As the trade relations of the countries develop, the importance of logistics and the logistics processes and document management has also increased. In order to manage time effectively and efficiently during logistics and cargo processes and to prevent loss of goods, time and money that some measures have been taken. For this purpose, it is thought that the ICS 2 process which is planned to reduce the waiting time at the customs and to carry out healthy and safe customs processes in advance will make an economic contribution to the EU countries.

1- Security of supply chains and transport (e.g. air cargo) - Safety, health and security of EU citizens and the internal market while facilitating the free flow of legal trade across the EU's external borders. ICS2 is the EU's new advanced cargo information system supporting the implementation of this new customs safety and security pre-arrival program and regulatory regime.

2- Classifies risky shipments according to the degree of risk in customs, determines customs control measures, strict inspections for risky shipments, verifies documents. ICS2 provides smooth communication, data sharing, cooperation and transparency in imports. It includes functions such as ensuring codification of EU legislation and strict implementation measures, facilitating political trade activities, ensuring the security of the EU customs area.

Freight forwarding and logistics companies, sea rail and road transport, representatives of all affected EOS sectors will be affected (Keleci, 2024). In the Figure below was give sectors affected by its implementation from ICS 2.

Figure 3. ICS2, Sectors Affected by Its Implementation Search (Derneği, 2024)

Figure 5. ICS2, Sectors Affected by Its Implementation Search: (Comission, Taxation, 2024)

According to Figure 5 ICS2, effects these sectors: Postal operations, express carriers, freight forwarding logistics providers, air carriers, maritime implementation, railroad carriers, business receiving goods in EU, consignees, importers.

There is also a cost to implementing policies aimed at preventing tax evasion and in this respect, tax evasion also causes a loss of efficiency in the economy. The resources that taxpayers allocate for consultancy services etc. for actions contrary to tax regulations and the expenses incurred by the tax administration to reveal tax losses are clear indicators of the loss of efficiency (Slemrod, 2007).

ICS2 provides the following conveniences:

1. ICS2 Simplifies Arrival Notifications:

There is a pre-arrival notification process where goods going to the EU customs area are sent electronically with detailed notifications. These notifications cover important information such as the nature, quantity, value, origin and intended recipient of the imported goods. These notifications made through a user-friendly interface are made in a timely manner before the goods arrive at the EU border that allowing for smoother customs clearance.

2. Authorization with Risk Analysis:

ICS2's robust risk analysis mechanism allows customs authorities to conduct comprehensive assessments of each incoming shipment. Taking into account factors such as the type of goods, their origin and the importer's compliance history, ICS2 categorizes shipments into high-risk, medium-risk or low-risk categories. This classification guides subsequent customs control measures, providing a targeted approach to security and safety measures.

3. High Customs Control Measures:

ICS2's customs controls of high-risk goods or shipments in accordance with the law, cooperating with regulatory authorities and ensuring control

4. Facilitating Communication and Data Sharing: Increasing transparency

ICS2 enables seamless communication and data sharing between stakeholders in imports. It further strengthens cooperation, security and compliance efforts among EU institutions.

5. Ensuring Compliance and Enforcement: Customs authorities ensure the integrity and security of the EU customs area by ensuring compliance through inspections, controls and penalties in cases of non-compliance.

It requires the person to declare the safety and security data related to the activities within the scope of customs legislation through summary declaration with ICS2 is an electronic customs system (TAXUD, 2022).

3.2. Disadvantages of ICS2

In ICS2, thanks to artificial intelligence and machine development and tax calculation can be maintained automatically and the carrier must be very careful in high expansions. There will be a penalty for those who report incomplete or late receipt of ICS2. In this case which leads to delays in customs clearance and customs authorities and customs policies. There are regulations regarding the imposition of the penalty (Icustoms, 2024). According to the official records of the General Directorate of Taxation and Customs Union on January 29, 2024, the EU Carbon Border Adjustment Mechanism (CBAM) and Import Control System (ICS2) documents could not be submitted by the operators due to a technical malfunction in the system. General Directorate of Taxation and Customs Union Carriers who were unable to make Pass Registration and Import Control System 2 (ICS2) Pass Registration were given time and requested to submit this information after the technical malfunction was resolved within 30 days. If this security system which depends on artificial intelligence and machine automation, malfunctions that there are carriers that have problems in transit.

The Commissions acknowledged that they experienced technical problems that could not provide the submitted EU Carbon Border Adjustment Mechanism (CBAM) and Import Control System 2 (ICS2) data and reports (KPMG, 2024).

Individuals who live outside the EU and send goods from the EU to the EU in transit may be penalized if they do not provide accurate information about their shipments. In this system, all stakeholders have great responsibility. Economic operators should be ready to handle the ICS2 data incorrectly with Entry Summary Declaration (ENS) in accordance with safety and security standards.

All exporters and producers will be indirectly affected in the system. Economic operators should ensure that all stakeholders are informed about this system. After March 1, 2023, air cargo carriers and express carriers will be required to provide electronic data sets for ENS and ICS 2. After June 3, 2024, road, sea, rail carriers and final recipients of all goods brought to customs will also be required to provide a fully developed electronic data set for ICS2 via electronic ENS. Carrier operators must ensure that their IT systems and software are compatible with ICS2 formats and standards. In addition, employees not being trained in this regard is also a disadvantage. If there is no electronic data set in ICS2 format, problems will arise. A separate budget should be allocated for employee training. Employees should be trained on how to solve problems in the event of a possible problem. Business partners will need to establish a communication line with customers about ICS 2. Incomplete and incorrect information from the customer will cause problems. Your customers and business partners should provide accurate and complete information about.

4. Turkey and Customs Union

The importation of goods without paying customs duties partially or completely through deceptive transactions and behaviors is regulated in the 3/2nd paragraph of the Anti-Smuggling Law. The crime regulated in this paragraph is a crime committed with the aim of paying less tax or not paying any tax through deceptive transactions and behaviors. In other crimes, in addition to not paying tax, the aim of evading trade policy measures may also be in question (Bülbül & Özay, 2016). In Turkey, the Ministry of Trade has put the Union Customs Code (BGK) into effect as of May 1, 2016, of the European Union (EU). It is reported that customs administrations in Turkey are working on conducting all customs transactions including all data transfer and storage transactions between economic operators that in an electronic environment and that information technology systems developed for this purpose are being gradually implemented (TIM, ICS2, 2024).

Although the Turkey-EU Customs Union is still in effect but it has lost its relevance. Since the Customs Union entered into force in 1996, Turkey-EU relations have changed. The Turkey-EU Customs Union is still in force but has lost its relevance. The EU's trade relations which have expanded from 15 to 27 member countries need to be reexamined (Yanarışık, 2023).

According to Article 12 of the Customs Union Decision No. 1/95, Turkey has complied with the Community's rules on common rules for imports and common rules for imports from certain third countries also the administration of quantitative restrictions and measures against unfair commercial practices of quotas and tariff quotas in exports, quantitative restrictions applied to third countries in the textile and ready-to-wear sector and inward and outward processing regimes as of January 1, 1996. According to Article 16 of the Decision No. 1/95, Turkey has started to make agreements like the Free Trade Agreements (FTAs) that the EU has made with various countries to comply with the Common Trade Policy (Union C., 2024). Under the Import Control System 2, the third phase of the European Union (EU) pre-arrival security and safety system for customs, all goods (including mail and express shipments) transported to or from the EU by sea, inland waterways, roads and railways will be subject to new requirements (TIM, 2024)

Turkish Airlines has been requesting HS Code in E-AWB (E-Airway Bill of Lading) notifications for flights arriving in Europe since February 15, 2023. If the companies' software programs are compatible that there isn't problem but companies whose systems aren't compatible experienced problems. Citizens of the European Union (EU) must provide additional information for their safety and security at customs. It is necessary to have software systems to provide this information to avoid delays in shipments against high penalties. If a shipment is by air to or transiting through the EU, Northern Ireland, Norway and Switzerland so all shipments must: At least a six-digit Harmonized System (HSIP) code for each product in the shipment;

Accurate product description for each item in the shipment; (Harmonized or HS code) Recipient's Economic Operator Registration and Identification (EORI) number. These rules apply to all products (except documents) regardless of value. EORI stands for "Economic Operator Registration and Identification". In all kinds of customs operations such as export, import and transit in the European Union customs area, economic operators EORI number, statistics, and security are important for customs operations.

From 1st of March 2024 Highway, railway, on the seaway If information is not provided with the imported/exported goods that the shipment will not be delivered to EU member countries until they obtain this information. A minimum six-digit HS code must be given for each product.

The Harmonized System (HSIP) code is an internationally standardized system for identifying and classifying products. HS code**:** A Harmonized System (HS) code is a numerical customs code that classifies products on a universal level. For filing to EU Customs entities, the first 6 digits of the HS code are mandatory. EORI number: An Economic Operators Registration and Identification (EORI) number is an identification number that is required when exchanging information with EU customs entities. The inadequacy of technology in explaining long-term growth as an external factor has led to the emergence of internal growth models instead of this growth theory (Özer, 2012, s. 70) This model stated that technological developments would cause income inequality between countries (Yürek, 1997, s. 2)

The extent to which developments in foreign trade affect economic growth is discussed in the economic literature. In this respect, there are studies in the literature examining the effects of export and economic growth together. In recent years, the effects of IIT on economic growth have been questioned. Then, this issue has become a subject of research. In this section, studies on the relationship between IT and economic growth in national and international literature are included (Yağış, 2024).

Table 2. The Effects of Export and Economic Growth Literature

Author	Country-	Period	Method	Result
Wörz (2004)	45 Countries	1981-1997	Dynamic Panel	A Positive Result Was Found Between Export Products and Economic Growth
Falk (2009)	22 OECD Countries	1980-2004	Dynamic Panel	A Positive Result Was Found Between IIT and Economic Growth
Kılavuz & Topçu Altay (2012)	22 Developing Countries	1998-2006	Panel Data	A Positive Result Was Found Between High-Tech Manufacturing Industry Exports and Economic Growth
Turkey (2013)	53 Countries	1995-2008	Regression Analysis	A Positive Relationship Between Information and Communication Technologies and Economic Growth
Telatar Et. (2016)	Turkey	1996-2015	Cointegration and Causality	It was found that HTE and Economic Growth have a Causality Relationship.
Isik & Kilinc (2016)	Selected Countries Dynamic	1990-2011	Panel Data	A Positive Result was Found Between Innovation and Economic Growth
Kizilkaya (2016)	Brics	2001-2011	Panel Data	A Positive Result was Found Between RDE and Trade Openness HTE
Alper (2017)	Turkey	1990-2015	Causality	Causality was Found from Economic Growth to RDE and HTE.
Usman (2017)	Pakistan	1995-2014	OLS	IIT and Economic Growth Found to be Correlated
Konak (2018)	OECD	1992-2016	Panel Data	Turkey Lags Behind Other Countries in High Technology Export
Kabaklarlı Et. (2018)		OECD 1989-2015	Panel Data	A Relationship Between IIT and Economic Growth is Found
Erdil Şahin (2019)	Turkey	1989-2017	Causality	A Positive Result is Found Between IIT and Economic Growth
Şeker & Özcan (2019)	Turkey	1986-2016	Time Series	A Causality is Found Between IIT and Economic Growth
Buchinskaya & Dyatel (2019)	38 European Countries	1992-2016	Panel Data	A Relationship is Found Between IIT and Economic Growth
Köse & Gültekin (2020)	OECD	1996-2017	Panel Data	A Bidirectional Causality is Found Between IIT and Economic Growth
Doru & Dabakoğlu (2021)	11 Transitions Country	1995-2018	Panel Data	A Positive Result Was Found Between IIT and Economic Growth
Ersin Et. (2022)	35 OECD Countries	1992-2016	Dynamic Panel Threshold Regressions and Bootstrapping Threshold	It Was Found That IIT Has a Positive Effect on Economic Growth
Sojoadi & Banghbanpour (2023)	30 Developing and 30 Developed Countries	2007-2022	Panel Causality	Causality from Economic Growth to IIT Was Found
Shadab & Alam (2024)	UAE	1991-2020	Causality Analysis	Causality from IIT to Economic Growth Was Found.

Search (Yağış, 2023).

ICS 2 application which was put into practice because of the application of developments in information technology in customs transactions has begun to be implemented to prevent smuggling and ensure safe passage through customs. With the use of technology, evasion of taxes at customs can be prevented and economic contribution can be made.

5. Research Method

The research used quantitative research method. In France, Germany, Switzerland and Sweden, where ICS 2 was implemented in 2021 and the applications were examined for the years 2017, 2018 and 2019 before the ICS 2 implementation and the years 2022, 2023, 2024 after the ICS 2 implementation and the efficiency of the application was evaluated. Data on a commodity group basis was requested from some statistics centers abroad but our request was rejected. There upon, current data on the selected export groups in question were requested from the Ministry of Trade of the Republic of Turkey for the specified countries and obtained. The delivery times determined for these groups are the "Average Delivery Times" obtained from Airline Cargo companies. The reasons for choosing the countries Germany, France, Sweden and Switzerland for the research are as follows;

1- They are the countries with the most exports from Turkey to the European Union countries by air.

2- These countries have long distances to our country and developed economies also effective weather conditions (especially in the winter seasons).

3- In these countries, there are very high level services related to the air transportation system (Airline, Airport, Ground Services etc.).

4- There are some risks related to security and delay situations on the route and corridor.

Table 3 shows the export figures of HS7, HS 8, HS 30, HS 71 products in France, Germany, Switzerland, and Sweden where ICS 2 is implemented in 2017, 2018 and 2019, and the export figures of HS7, HS 8, HS 30, HS 71 products in 2022, 2023 and 2024.

HS Codes & Products

HS 07 - Edible Vegetables and some roots and tubers
HS 08 - Edible fruits, nuts, citrus and melon peels
HS 30 - Pharmaceutical Products
HS 71 - Pearls, precious stones and metal products, coins

The reasons for choosing the HS 07, HS 08, HS 30, HS 71 product groups for the research are as follows;

1- Since the shelf life of the products is short and there is a risk of spoilage, they must be delivered to the customer as quickly as possible.
2- Transportation must be carried out with high security, minimum risk factors and a damage rate close to 0.
3- The elapsed time causes the financial value of the product to decrease and the chance of sale to decrease.
4- Since a large amount of cold storage will be needed to hold the products during the European Union customs procedures. The products must be customs processed and delivered quickly. **Table 4,** shows the comparison of exports from Germany, Sweden, Switzerland and France to the European Union in 2017, 2018, 2019 and 2022, 2023, 2024 using the ***Levene's*** Homogeneity of Variances test.

T.A. - Total EU Airline
Te - Total EU Export
G.E.T. - Germany EU Total
F.E.T. - France EU Total
Sw.E.T. - Sweden EU Total
S.E.T. - Switzerland EU Total
HTG - Germany HS Total
HTF - France HS Total
HTSw - Sweden HS Total
HTS - Switzerland HS Total

Levene's Test was performed to analyze to homogeneity of variances assumption. If the test result of the variables taken into the homogeneity test is at the 0.10 level of significance (asymp. Sig.) p<.10, the homogeneity hypothesis is rejected. Table 4 shows Levene test results. Levene's Test results show that FET, H8Sw, H8S, H30G, H30Sw, H30S, HTF didn't provide variance homogeneity but it was determined that the remaining 20 variables provided the homogeneity assumption. Total 19 variables provided assumptions.

Shapiro-Wilk test was performed to analyze whether the research data showed a normal distribution. **Table 5** shows Normality One-sample Shapiro-Wilk test is a test used to test whether the hypotheses are significant or not and whether the values of the variables are normally distributed. If the test result of the variables taken into the normality test is at the 0.10 level of significance (asymp. Sig.) p<.10, the hypothesis is rejected and the distribution is decided to be non-normal.

Shapiro-Wilk test was performed to test the normality assumption. P value of tests is p≥.10 ensures that the hypothesis is accepted. The distribution does not exhibit a significant difference from the normal distribution. Test results show that other then **Te** all variables provided normality assumption.

ANOVA was applied to these 19 selected variables. Table 6 shows the ANOVA results.

Table 3. ICS 2 (Air Turkiye - EU Export) (X1.000)

TOT.EU.AIRLINE	TOT. EU EXP.	AIRLINE EXP.	Germany	France	Sweden	Switzerland	INCOTERMS	Average Delivery Time (Hour)
9.994.137	**67.987.332**	**2017**	**167.594.989**	**18.756.121**	**3.013.064**	**128.098.993**	**FOB**	51 Hour
		HS 07	24.438	118.949	1.312	124.019		
		HS 08	11.290	891	1.101	7.353		
		HS 30	351.351	27.215	8.476	178.807		
		HS 71	17.160.116	1.816.710	304.578	13.101.785		
		Total	**$ 17.547.195**	**$ 1.963.765**	**$ 315.467**	**$ 13.411.964**		
6.171.107	**77.429.205**	**2018**	**182.140.088**	**21.155.141**	**3.017.980**	**953.164.182**	**FOB**	51 Hour
		HS 07	31.173	129.237	522	96.687		
		HS 08	14.538	9.013	1.019	2.647		
		HS 30	303.081	21.327	2.477	111.899		
		HS 71	14.167.773	1.526.487	236.515	75.755.952		
		Total	**$ 14.516.565**	**$ 1.686.064**	**2 $ 40.533**	**$ 75.967.185**		
6.299.220	**76.726.198**	**2019**	**123.318.301**	**16.672.597**	**4.195.282**	**242.539.405**	**DDU**	46,5 Hour
		HS 07	22.103	95.732	1.927	78.237		
		HS 08	11.765	9.156	1.484	3.563		
		HS 30	307.077	19.638	101	170.862		
		HS 71	9.795.819	1.245.961	341.340	19.684.077		
		Total	**$ 10.136.764**	**$ 1.370.487**	**$ 344.852**	**$ 19.936.739**		
8.388.196	**103.049.092**	**2022**	**2. PART 126.609.651**	**24.577.093**	**5.822.518**	**180.961.529**	**DDP**	36.5 Hour
		HS 07	22.312	45.565	1.526	43.988		
		HS 08	9.320	1.341	2.189	5.174		
		HS 30	1.449.118	32.981	1.576	575.187		
		HS 71	8.825.275	1.920.688	468.662	14.105.919		
		Total	**$ 10.306.025**	**$ 2.000.575**	**$ 473.953**	**$ 14.730.268**		
10.219.598	**104.283.598**	**2023**	**107.535.752**	**23.659.463**	**5.889.915**	**466.083.571**	**DDP**	33 Hour
		HS 07	44.697	95.324	5.399	101.450		
		HS 08	10.540	8.799	13.974	5.459		
		HS 30	197.004	54.350	1.456	237.193		
		HS 71	10.479.827	2.202.741	566.884	46.171.038		
		Total	**$ 10.732.068 $**	**$ 2.361.214 $**	**$ 587.713 $**	**$ 46.515.140**		
7.836.289	**80.289.847**	**2024 (10 months)**	**104.161.616**	**29.116.692**	**4.034.004**	**75.483.907**	**CIF**	33 Hour
		HS 07	23333	44546	1982	53111		
		HS 08	6 811	2013	2002	4121		
		HS 30	100.596	63.940	2.255	45.672		
		HS 71	10.191.676	2.774.965	393.530	7.377.551		
		Total	**$ 10.322.416**	**$ 2.885.464**	**$ 399.769**	**$ 7.480.455**		

Table 4 Test of Homogeneity of Variance Homogeneity of Variances Test (**Levene's**)

	F	df1	df2	p
TA	3.2567	1	4	0.145
Te	0.3353	1	4	0.594
GET	3.3020	1	4	0.143
FET	5.3171	1	4	0.082
SwET	0.1761	1	4	0.696
SET	3.4110	1	4	0.138
H7G	3.0989	1	4	0.153
H7F	1.2070	1	4	0.334
H7Sw	4.3002	1	4	0.107
H7S	1.1592	1	4	0.342
H8G	1.0447	1	4	0.365
VH8F	0.2124	1	4	0.669
H8Sw	14.8016	1	4	0.018
H8S	9.7832	1	4	0.035
H30G	14.5109	1	4	0.019
H30F	2.6161	1	4	0.181
H30Sw	6.3045	1	4	0.066
H30S	5.1950	1	4	0.085
H71G	1.4438	1	4	0.296
H71F	3.9237	1	4	0.119
H71Sw	0.0615	1	4	0.816
H71S	1.8706	1	4	0.243
HTG	2.5576	1	4	0.185
HTF	6.0603	1	4	0.070
HTSw	0.2739	1	4	0.628
HTS	1.8568	1	4	0.245
TS	1.2308	1	4	0.329

First we planned to apply ANOVA (Analysis of Variance) to determine whether there is a significant difference between the results of the 2 application periods based on countries and commodity groups that the assumptions of ANOVA. Since the significant value of the values in Table 4 and 5 is p>0.10, the ANOVA test was performed, Normality assumption and equality of variances were tested using SPSS 24 and the Open-Source Code "Jamovi 2.3.24" was used.

Table 5 Test of Normality Normality Test (Shapiro-Wilk)

	W	p
TA	0.890	0.316
Te	0.764	0.027
GET	0.952	0.758
FET	0.907	0.420
SwET	0.917	0.484
SET	0.902	0.385
H7G	0.932	0.592
H7F	0.906	0.412
H7Sw	0.940	0.663
H7S	0.991	0.992
H8G	0.887	0.301
VH8F	0.925	0.543
H8Sw	0.836	0.121
H8S	0.913	0.458
H30G	0.850	0.157
H30F	0.932	0.592
H30Sw	0.929	0.571
H30S	0.919	0.497
H71G	0.989	0.988
H71F	0.933	0.607
H71Sw	0.925	0.543
H71S	0.844	0.141
HTG	0.975	0.925
HTF	0.938	0.639
HTSw	0.928	0.566
HTS	0.845	0.142
TS	0.878	0.259

Note. A low p-value suggests a violation of the assumption of normality

According to ANOVA results, there was a difference in France in the ICS2 application period for the H7 coded product group. A difference was determined only in Germany for the H8 coded product group. A significant difference was determined for Sweden for the H71 coded product group. When the totals of H7 – H8 – H30 – H71 were taken into account, it was determined that the ICS2 application created a difference in Sweden as well. In addition, it was obtained that the two periods were different in TS which shows average delivery times which is meaning that the ICS2 application significantly reduces the average delivery time.

Alpha type error was taken as 10% in the tests. The tests will be carried out at a 90% confidence level in the research. A low p-value suggests a violation of the assumption of equality of mean. The ANOVA test result is given in the Table 6.

Table 6. ANOVA One-Way ANOVA (Welch's)

	F	df1	df2	p
TA	0.173	1	2.86	0.706
GET	5.577	1	2.61	0.112
SwET	16.498	1	3.92	0.016
SET	0.501	1	2.78	0.534
H7G	0.633	1	2.64	0.492
H7F	7.385	1	3.41	0.063
H7Sw	2.207	1	2.47	0.252
H7S	1.929	1	2.93	0.261
H8G	6.802	1	3.51	0.068
VH8F	0.364	1	3.90	0.580
H71G	1.844	1	2.81	0.273
H71F	4.290	1	2.57	0.145
H71Sw	21.975	1	3.99	0.009
H71S	0.325	1	3.23	0.606
HTG	1.701	1	2.35	0.305
HTSw	19.539	1	3.88	0.012
HTS	0.320	1	3.24	0.608
TS	73.923	1	3.48	0.002

This contradictory situation directs us to alternatives that do not require assumptions. For this, the Kruskal-Wallis test which is the non-parametric alternative of one-way Analysis of Variance was applied. The test results are summarized in the Table 7.

Table 7 Kruskal-Walli Hypothesis Test Summary

Null Hypothesis	Test	Sig.	Decision
The distribution of TA is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,513	Retain the null hypothesis.
The distribution of Te is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,050	Reject the null hypothesis.
The distribution of GET is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,127	Retain the null hypothesis.
The distribution of FET is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,050	Reject the null hypothesis.
The distribution of SwET is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,050	Reject the null hypothesis.
The distribution of SET is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,513	Retain the null hypothesis.
The distribution of H7G is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,513	Retain the null hypothesis.
The distribution of H7F is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,050	Reject the null hypothesis.
The distribution of H7Sw is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,127	Retain the null hypothesis.
The distribution of H7S is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,275	Retain the null hypothesis.
The distribution of H30G is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,513	Retain the null hypothesis.
The distribution of H30F is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,050	Reject the null hypothesis.
The distribution of H30Sw is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,827	Retain the null hypothesis.
The distribution of H30S is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,513	Retain the null hypothesis.
The distribution of H71G is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,275	Retain the null hypothesis.
The distribution of H71F is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,050	Reject the null hypothesis.
The distribution of H71Sw is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,050	Reject the null hypothesis.
The distribution of H71S is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,513	Retain the null hypothesis.
The distribution of H8G is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,050	Reject the null hypothesis.
The distribution of VH8F is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,513	Retain the null hypothesis.
The distribution of H8Sw is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,050	Reject the null hypothesis.
The distribution of H8S is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,513	Retain the null hypothesis.
The distribution of HTG is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,513	Retain the null hypothesis.
The distribution of HTF is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,513	Retain the null hypothesis.
The distribution of HTSw is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,050	Reject the null hypothesis.
The distribution of HTS is the same across categories of D.	Independent-Samples Kruskal-Wallis Test	,513	Retain the null hypothesis.

Kruskal-Wallis Tests (One-Way ANOVA Non-parametric Alternative)

Te (Total EU Export) there is a significant increase between the period of 2017, 2018, 2019 before ICS2 and between the years of 2022, 2023, 2024 after ICS2. A significant increase is also seen for **F.E.T**. between the same periods. There is also a significant increase in **Sw.E.T.** in the same periods.

The significant difference found for France the **HS 07** group is due to the return of fruit and vegetable exports to this country.

This decrease is due to the characteristics of the product group. A similar situation is seen in Germany and Sweden for the **HS 08** group.

In the **HS 30** group, ICS 2 created a significant increase for France.

The **HS 71** group creates a significant increase in France and Sweden.

A significant increase occurs in Sweden after ICS 2 when the total export figures for these 4 product groups are considered. It is also known theoretically that not all of the significant increases that occur are due to ICS 2.

The number of data and observations will increase and more reliable multivariate comparisons will be possible when the implementation period of ICS 2 is extended. Since the number of variables will also be a separate constraint in such multivariate comparisons that the number of observations for each period (before and after ICS 2) needs to be increased.

In our study, only the 6 criteria which is the minimum number of observations for tests at the level of 10% for a single variable (separate variables) could be met. Because the implementation start date was very close.

In general, the delivery time is shortening and the expected significant results have emerged in product groups that need to be produced in accordance such as **HS 30** and **HS 71**.

6. Conclusions

The ICS2 system isn't a system that includes the creation of an import declaration for free circulation. It is an electronic customs system based on detailed cargo information and risk analysis that requires economic operators to submit PLACI data to EU Customs Administrations before loading in shipments to third countries directly or in transit to the EU and ENS data before arrival in the country of destination. It is implemented in Switzerland, Norway and Northern Ireland and in 27 EU member states. Economic operators including postal operators, express cargo, air cargo transportation, maritime, rail and road transportation that consignees in the EU and logistics companies will be affected. As of March 15, 2021, air cargo transportation has been implemented in Switzerland, Norway and Northern Ireland in the EU in the first phase, preloading and air mail transportation. It has been implemented in air general cargo transportation and mail transportation after March 2023 with the second phase.

It implemented for maritime transportation after June 3, 2024. The third phase is planned to be implemented in maritime, rail and road transportation. It will be planned to be implemented in the EU for road and rail transport as of April 1, 2025.

Data entry has also started for postal operators, express cargo, and air cargo transportation. As of June 3, 2024, for maritime transport, it is mandatory to transmit ENS information to the system before the shipment arrives at EU customs after June 3, 2024.

Thanks to the ICS 2 system that cargo information will be transmitted and early intervention of customs authorities will be possible by performing risk analysis and security controls will be able to intervene at the most appropriate point of the supply chain that facilitating trade by controlling the legal trade flow outside the EU - facilitating international customs procedures

- Simplifying the exchange of information between economic operators and EU Customs Administrations,
- Accelerating the processing processes thanks to the pre-arrival security notifications and the ability to determine the risk criteria of the cargo carried in advance.

The ENS document is an electronic summary declaration document. It is a mandatory document that must be submitted before the shipments to be made to the EU or to third countries in transit from the EU are delivered to the EU Customs Administrations under the responsibility of the carrier or a representative to be appointed in his place.

Information regarding the goods in question such as the sender, receiver, seller, manufacturer and their addresses, telephone numbers and tax numbers etc. (6-digit HS code, description, weight, container information and freight charges, etc.), location information (reception place, loading, unloading, delivery, shipment route and route of the means of transport, etc.), transportation information (transport vehicle information, departure and arrival dates and times, etc.) and supporting document information (delivery note, invoice, etc.) must be submitted.

Data regarding air cargo transportation, express cargo and postal shipments and shipments going to EU member countries or transiting from the EU to third countries are submitted to customs as PLACI data (i.e. 7+1) before loading. The information also called PLACI data is in the form of a 7+1 data set and is requested to ensure security at customs. This data includes the name/title of the sender, the address of the sender (including postal code), the name/title of the receiver, the address and EORI number of the receiver, detailed description of the goods and 6-digit GTIP Code, weight, quantity and HAWB number if any.

For shipments in sea, railroad and air transportation modes, the entire ENS data set must be submitted and the arrival notification must be made and the procedures for presenting cargo transportation shipments to customs must be carried out. The carrier preparing the ENS document is uploaded to the relevant EU system (https://customs.ec.europa.eu/gtp) as a Single Filing or Multiple Filing.

In Multiple Filing transactions consisting of two or more ENS files, the carrier, intermediaries and the final recipient are jointly responsible.

The ENS document is an electronic summary declaration document. It is a mandatory document that must be given to the carrier or a representative to be appointed in his place in all shipments before they reach the EU Customs Administrations. The sender, recipient, seller, manufacturer and their address, telephone also tax numbers etc. information regarding the traded goods (6-digit HS code, description, weight, container information and freight charges, etc.), location information (place of acceptance, loading, unloading, delivery, shipment route and route of the means of transport, etc.), transportation information (transport vehicle information, departure and arrival dates and times, etc.) and supporting documents (delivery note, invoice, etc.) should be submitted.

While the ICS2 system is mandatory for all cargo, courier and postal shipments that will transit and arrive in European Union countries (including Norway, Switzerland and Northern Ireland), there is an exception for postal letter shipments, diplomatic shipments and cargo carried for military purposes. ENS is not requested as an exception in these shipments. The exporter is responsible for the complete and accurate transmission of PLACI and ENS data of the goods within the scope of the shipment to the carriers.

In ICS2, economic operators are responsible for electronically entering PLACI and ENS data related to the goods into the EU customs system within the time limit. The ultimate responsibility lies with the carrier. The MRN number is an arrival summary declaration number. The Movement Reference Number (MRN) is a number assigned by the customs administration of the member state to which the ENS document is transmitted that based on the master bill of lading which after the ENS document is uploaded to the ICS2 system and approved, accepted and recorded.

With this number, import clearance procedures are initiated after the shipment arrives at the EU customs. In the absence of the MRN number, customs penalties may be applied and delays may occur in the import clearance processes.

The Economic Operator Registration and Identification Number (EORI) is a number valid throughout the European Union and is the number given to economic operators by the competent customs administration of a member state.

The economic operator will use this number in customs procedures or in all transactions with a customs authority. There is no obligation to obtain an EORI number for goods not destined for the EU and tax numbers must be written.

ICS 2 is seen as a security measure for all carriers entering the member countries of the European Union, for the European Union. The development of artificial intelligence of information technology, the Internet of things and block chain technology will be gradually placed in logistics customs' transactions. For this, it is important for everyone from transport operators to all stakeholders to establish their technical infrastructure also train their personnel for this purpose and provide uninterrupted energy service in customs. While the new world order is implementing ICS2 in customs today and it is trying to reduce energy time efficiency carbon footprint by sending documents and making payments with block chain in making virtual meetings with meta verse and smart contracts by sharing this information between customers. It is necessary for all logistics stakeholders to convey the information correctly that provide personnel training, prepare the technical infrastructure and convey the necessary information correctly on time. In case of incorrect information being provided, the information being hidden by the carrier and the customer and penal sanctions are applied also customs transactions cannot be carried out. According to technological advances, the Turkish Anti-smuggling Law should be applied to those who provide false and unfounded information in ICS2 transactions and those who do not fulfill the responsibilities of the carrier in the Turkish Law should be subject to penal sanctions. Updates and codifications should be made in our legal legislation and the "Regulation on the Non-Use of Crypto Assets in Payments" published in the Official Gazette dated April 16, 2021 and numbered 31456 should be updated for international payments.

According to our research results, there is a significant increase in Te (Total EU Export). There is also a significant increase in F.E.T. There is also a significant increase in Sw.ET. The significant difference found for the HS 07 group is due to the return of fruit and vegetable exports to this country.

This decrease is due to the characteristics of the product group. A similar situation is seen in Germany and Sweden for the HS 08 group.

In the HS 30 group, ICS 2 created a significant increase for France.

The HS 71 group creates a significant increase in France and Sweden.

A significant increase occurs in Sweden after ICS 2 when the total export figures for these 4 product groups are considered. It is also known theoretically that not all of the significant increases that occur are due to ICS 2.

The number of data and observations will increase and more reliable multivariate comparisons will be possible when the implementation period of ICS 2 is extended. Since the number of variables will also be a separate constraint in such multivariate comparisons that the number of observations for each period (before and after ICS 2) needs to be increased. In our study, only the 6 criteria which is the minimum number of observations for tests at the level of 10% for a single variable (separate variables) could be met. Because the implementation start date was very close.

In general, the delivery time is shortening and the expected significant results have emerged in product groups that need to be produced in accordance such as HS 30 and HS 71.

Ethical Approval

The information obtained in this research is summarized within the framework of ethical rules.

Thanks

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Conflicts of Interest

There is no conflict of interest regarding the publication of this paper.

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Prioritizing Risk Mitigation Strategies in Air Cargo Freight Operations: A Fuzzy TOPSIS Approach

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Abstract

This study explores the prioritization of risk mitigation strategies in air cargo operations using a Fuzzy TOPSIS methodology. Air cargo operations face multifaceted risks, including operational inefficiencies, cybersecurity threats, regulatory compliance challenges, and environmental concerns. To address these, a structured decision-making framework was developed, integrating expert evaluations with fuzzy logic to rank mitigation strategies across ten criteria, such as cost-effectiveness, operational efficiency, and scalability. Enhanced Data Security Measures emerged as the top-ranked strategy, reflecting the critical importance of cybersecurity in modern logistics. Other highly prioritized strategies, including Resilience Building for Disruptions and Safety Enhancement Protocols, underscore the need for operational stability and safety in a rapidly evolving industry. The study demonstrates the practical applicability of Fuzzy TOPSIS in handling uncertainty and subjectivity in risk management while providing actionable insights for practitioners. Recommendations are offered for the implementation of prioritized strategies and the integration of emerging technologies, such as real-time analytics and AI-driven decision-making models. The findings contribute to advancing the field of risk management in air cargo operations and highlight areas for future research, including dynamic risk assessment and the integration of complementary MCDM techniques.

1. Introduction

Air cargo is a cornerstone of global trade, facilitating the rapid and reliable transportation of goods across international borders. Its role has become increasingly critical in an era where speed and efficiency are paramount to meeting the demands of global supply chains. From high-value electronics to perishable goods, air cargo ensures that time-sensitive products reach their destinations without delay, supporting economic growth and market competitiveness (Merkert, 2023; Sales & Scholte, 2023). The rising complexity of international commerce, driven by globalization and e-commerce, underscores the need for efficient air cargo systems. However, the sector faces significant challenges, including operational inefficiencies, delays, security breaches, and environmental concerns, which collectively threaten the seamless functioning of supply chains (Bunahri et al., 2023; Tseremoglou et al., 2022). Addressing these risks is essential for maintaining the reliability and resilience of the global logistics network.

The importance of effective risk management in air cargo operations has been highlighted by recent global crises, such as the COVID-19 pandemic, which exposed vulnerabilities in supply chains worldwide. These disruptions underscored the need for robust mitigation strategies to ensure continuity in air cargo operations and minimize the cascading effects of delays and disruptions on businesses and consumers (Hohenstein, 2022; Can Saglam et al., 2021). However, despite the growing recognition of risk management's critical role, the sector lacks structured and systematic methodologies for prioritizing risk mitigation strategies. Current approaches often fall short in addressing the complex, dynamic, and uncertain nature of air cargo operations, leaving operators ill-equipped to navigate emerging risks effectively (Sahoo et al., 2022; Dauer & Dittrich, 2022).

The inherent complexities of air cargo risk management are further compounded by the need for quick and precise decision-making in scenarios such as cargo handling optimization, disruption management, and compliance with evolving regulations. Traditional risk management frameworks struggle to accommodate these challenges, particularly in the face of rapid technological advancements and increasingly interconnected supply chain networks (Hong et al., 2025; Esmizadeh & Mellat Parast, 2021). Advanced decision-making tools, such as Multi-Criteria Decision-Making (MCDM) methodologies enhanced with fuzzy logic, offer a promising solution by systematically evaluating and ranking strategies under conditions of uncertainty.

These tools provide a nuanced and reliable approach to decision-making, capturing the inherent vagueness of expert judgments and operational complexities (Mahdavi et al., 2008; Kaya & Kahraman, 2011).

This study addresses the gap in the literature by proposing a Fuzzy TOPSIS-based model for prioritizing risk mitigation strategies in air cargo operations. The model integrates expert input with a robust analytical framework, providing a structured approach to evaluate key risks, such as operational delays, cybersecurity threats, and environmental challenges. By incorporating fuzzy logic, the model accommodates the uncertainties and ambiguities inherent in expert evaluations, ensuring a more reliable and adaptive decision-making process (Yan et al., 2022; Göçmen, 2021). The study identifies and evaluates critical risks affecting air cargo operations and develops a methodology to prioritize mitigation strategies that align with industry requirements and global trends.

The research draws on the expertise of professionals from logistics, supply chain, and risk management sectors, ensuring that the findings are both theoretically grounded and practically applicable. By focusing on the critical risks and employing a structured methodology, the study not only advances the academic discourse on risk management but also provides actionable insights for practitioners. These insights aim to enhance the resilience, efficiency, and sustainability of air cargo operations, addressing the multifaceted challenges faced by operators in today's interconnected and risk-prone environment (Richey Jr et al., 2023; Giuffrida et al., 2021). Through the prioritization of mitigation strategies, the study offers a practical framework for strengthening the robustness of air cargo operations and ensuring their continued role in supporting global trade.

2. Literature Review

2.1. Risk Factors in Air Cargo Freight Operations

Air cargo freight operations face a multitude of risks that can significantly disrupt supply chain performance. Operational risks such as cargo delays, mismanagement of cargo loads, and insufficient capacity planning are recurring issues in the air cargo industry (Sencer & Karaismailoğlu, 2022; Mesquita & Sanches, 2024). Delays, often caused by weather disruptions, mechanical failures, or inefficient terminal operations, can result in substantial financial losses and reputational damage for carriers (Han et al., 2022). Capacity mismanagement, particularly during peak demand periods, further exacerbates these challenges by creating bottlenecks and reducing operational efficiency (Gritsenko & Karpun, 2020).

Security risks, including theft, tampering, and the infiltration of contraband, present another significant challenge for air cargo operations. The high-value nature of goods transported via air freight makes these operations particularly susceptible to targeted security breaches (Sun et al., 2020). Cybersecurity threats, such as unauthorized access to cargo management systems, have also become more prevalent with the increasing digitization of logistics operations (Göçmen, 2021). The integration of advanced technologies, while improving efficiency, introduces new vulnerabilities that must be addressed through robust security protocols and monitoring systems (Mızrak & Akkartal,2023).

Environmental risks, including noise pollution, greenhouse gas emissions, and compliance with stringent environmental regulations, further complicate air cargo operations. Airports and freight carriers are under growing pressure to minimize their carbon footprints while maintaining high operational standards (Davydenko et al., 2020). Initiatives such as optimizing flight routes, adopting fuel-efficient technologies, and incorporating renewable energy sources in cargo operations have been explored to mitigate these environmental impacts (Archetti & Peirano, 2020). However, these solutions often require significant investment and strategic planning to implement effectively.

Previous studies have highlighted the importance of risk management frameworks tailored to the unique challenges of air cargo operations. For example, Dauer and Dittrich (2022) proposed an operational-risk-based approach for automated cargo delivery, emphasizing the need for scenario-specific risk assessment models. Similarly, De Oliveira et al. (2024) explored the integration of risk management practices into the import/export processes of supply chains, underscoring the interconnectedness of air cargo operations with broader logistics networks. These studies collectively emphasize the necessity for proactive and adaptive risk management strategies to ensure resilience and sustainability in air cargo operations.

2.2. Mitigation Strategies for Air Cargo Risks

Effective risk mitigation in air cargo operations is essential for ensuring the seamless functioning of global supply chains. Existing strategies often focus on enhancing operational efficiency, improving security protocols, and minimizing environmental impact. Proactive risk identification and real-time monitoring systems have been highlighted as critical tools for mitigating operational risks. For example, automated tracking technologies and predictive analytics are increasingly being employed to optimize cargo handling and reduce delays (Tanrıverdi et al., 2022; Angelelli et al., 2020). Additionally, the use of dynamic routing models helps carriers adapt to changing circumstances, such as adverse weather conditions or airport congestion, ensuring timely delivery (Archetti & Peirano, 2020).

In terms of security, the integration of advanced surveillance technologies and collaborative security frameworks has proven effective in mitigating threats like theft and smuggling. For instance, layered security systems that combine physical inspections with digital safeguards are widely adopted to secure high-value goods during transit (Han et al., 2022; Dauer & Dittrich, 2022). Furthermore, the application of blockchain technology for cargo documentation and tracking has been explored to enhance transparency and prevent data manipulation (Hohenstein, 2022). However, these solutions often face challenges related to scalability and interoperability across different systems and stakeholders.

To address environmental risks, air cargo operators are exploring sustainable practices, such as utilizing fuel-efficient aircraft and implementing green logistics strategies. Carbon offset programs and the adoption of alternative fuels are also gaining traction as viable solutions to meet environmental regulations and reduce emissions (Bartle et al., 2021; Davydenko et al., 2020). While these measures contribute to environmental sustainability, their implementation often involves high costs and operational adjustments, which can hinder widespread adoption.

Despite these advancements, gaps in prioritization methodologies persist. Traditional approaches to risk mitigation often rely on qualitative assessments that lack the precision and adaptability needed in dynamic air cargo environments (Mesquita & Sanches, 2024). For example, while many studies propose comprehensive risk management frameworks, they often fail to address how to prioritize multiple risks or mitigation strategies effectively. Additionally, there is limited research on incorporating expert judgment and real-time data into decision-making models (Richey Jr. et al., 2023; Kondratenko et al., 2020). The lack of structured, quantitative approaches to ranking mitigation strategies under uncertainty creates a critical gap in the literature.

Addressing these gaps requires innovative methodologies that combine multi-criteria decision-making (MCDM) tools with advanced data analytics. Fuzzy logic-based approaches, for example, offer a way to integrate subjective expert opinions with quantitative metrics, providing a more holistic framework for risk prioritization. Studies suggest that models like Fuzzy TOPSIS can bridge these gaps by evaluating and ranking mitigation strategies under uncertain and dynamic conditions, making them particularly suitable for complex systems like air cargo freight operations (Budak et al., 2020; Mahdavi et al., 2008). However, further research is needed to validate these models in practical scenarios and tailor them to the specific challenges of air cargo logistics.

2.3. Multi-Criteria Decision-Making (MCDM) in Risk Management

The application of Multi-Criteria Decision-Making (MCDM) methods has been pivotal in addressing the complexities of logistics and supply chain management, particularly in the domain of risk management. MCDM methodologies provide structured frameworks for evaluating multiple, often conflicting, criteria, enabling decision-makers to assess trade-offs and prioritize strategies effectively (Pournader et al., 2020; Hohenstein, 2022). In logistics and supply chain contexts, MCDM tools have been widely employed for tasks such as supplier selection, route optimization, and the prioritization of risk mitigation strategies. For instance, the Analytical Hierarchy Process (AHP) and the Best-Worst Method (BWM) have been extensively used to rank suppliers based on criteria such as cost, reliability, and environmental impact (Yalçın & Ayyıldız, 2024; Gao et al., 2023). Similarly, methods like PROMETHEE and ELECTRE have demonstrated their versatility in evaluating transportation options, showcasing their adaptability to a variety of decision-making scenarios (Tanrıverdi et al., 2022; Göçmen, 2021).

Fuzzy logic has emerged as a transformative extension to traditional MCDM methods, especially in addressing the uncertainties inherent in risk management. Conventional decision-making approaches often face challenges when dealing with imprecise or incomplete information—a common occurrence in logistics operations where subjective expert judgments play a critical role (Kaya & Kahraman, 2011; Kondratenko et al., 2020). Fuzzy logic overcomes these limitations by employing linguistic variables and fuzzy sets, enabling decision-makers to better navigate the nuances of uncertainty. For example, fuzzy extensions of AHP and TOPSIS have been employed to incorporate expert opinions and account for real-world complexities, significantly enhancing the robustness of risk assessments (Mahdavi et al., 2008; Budak et al., 2020).

Among MCDM methods, TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) has gained prominence for its simplicity and efficiency in ranking alternatives. The method involves identifying the ideal and anti-ideal solutions and calculating the relative closeness of each alternative to these benchmarks (Kaya & Kahraman, 2011). Its applications span various domains, including supply chain risk management, where it has been utilized to evaluate and prioritize mitigation strategies, assess supplier performance, and optimize logistics network designs (Tanrıverdi et al., 2022; Mesquita & Sanches, 2024). Fuzzy TOPSIS, an extension of the traditional method, further enhances decision-making by accommodating uncertainty and subjectivity in criteria weights and alternative evaluations (Mahdavi et al., 2008). Budak et al. (2020) demonstrated the effectiveness of fuzzy TOPSIS in selecting real-time location systems for humanitarian logistics, highlighting its adaptability to dynamic and complex environments.

Recent advancements in the fuzzy TOPSIS method have introduced further refinements to enhance its applicability. Intuitionistic fuzzy TOPSIS, as proposed by Boran et al. (2009), extends the traditional approach by incorporating intuitionistic fuzzy sets to handle higher degrees of uncertainty and vagueness. This methodology has been particularly useful in scenarios requiring group decision-making, such as supplier selection. Additionally, q-rung orthopair fuzzy TOPSIS represents a significant evolution of the method, providing an even more flexible framework for addressing complex decision-making scenarios. Pınar (2021) applied q-rung orthopair fuzzy TOPSIS to third-party logistics provider selection, demonstrating its ability to manage intricate criteria relationships. Further developments by Pınar and Boran (2022) utilized this approach in combination with other MCDM methods, such as CODAS, to evaluate 3PL service providers, showcasing its robustness and adaptability.

While these advancements have enhanced the capabilities of the fuzzy TOPSIS method, the effective application of such techniques requires careful consideration of criteria selection and weight assignment, often necessitating expert input. By integrating fuzzy logic into TOPSIS, decision-makers can address the limitations of conventional methods and establish a robust framework for managing the uncertainties and complexities inherent in risk management. The combination of quantitative rigor with qualitative insights positions fuzzy TOPSIS as a valuable tool for enhancing operational resilience and efficiency in logistics and supply chain management.

3. Research Methodology

3.1. Study Design

This study employs a mixed-methods approach, integrating qualitative and quantitative data collection. Expert evaluations are used to identify and weight key criteria for prioritizing risk mitigation strategies. The qualitative component involves gathering expert insights through structured interviews, while the quantitative analysis applies the Fuzzy TOPSIS methodology to evaluate and rank the identified strategies, ensuring a comprehensive and systematic assessment.

While traditional methods like AHP and PROMETHEE provide robust frameworks for multi-criteria decision-making, their deterministic nature limits their effectiveness in contexts involving high uncertainty. Fuzzy TOPSIS, in contrast, incorporates fuzzy logic, allowing for a more nuanced representation of expert opinions, making it particularly suited for the complex and uncertain environment of air cargo operations. Figure 1 demonstrates the steps of the analysis.

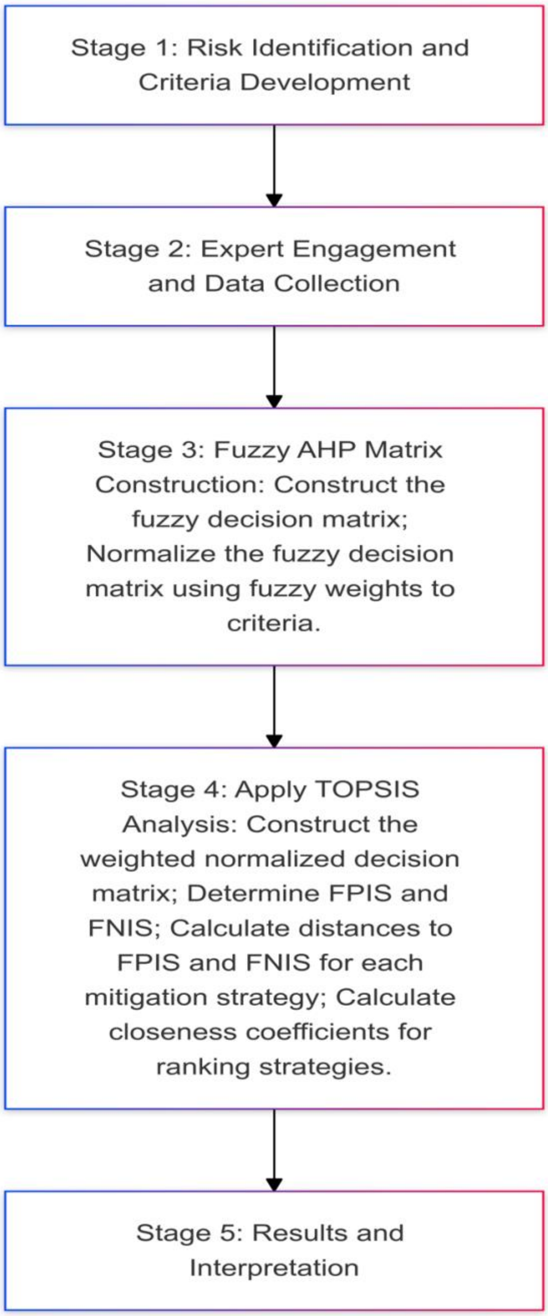

Figure 1. Workflow Chart

3.2. Identification of Risk Mitigation Criteria

The identification of appropriate risk mitigation criteria is critical for developing an effective decision-making framework. In this study, the criteria are categorized into key dimensions, including cost-effectiveness, operational efficiency, scalability, and regulatory compliance, which reflect the multifaceted nature of risk management in air cargo operations. These categories are widely recognized in the literature as essential for evaluating and prioritizing strategies in logistics and supply chain contexts (Hohenstein, 2022; Esmizadeh & Mellat Parast, 2021

Cost-effectiveness is a fundamental criterion, ensuring that mitigation strategies provide value while optimizing resource utilization. Studies emphasize the need for cost-efficient solutions, particularly in the competitive and cost-sensitive air cargo industry (Angelelli et al., 2020; Mesquita & Sanches, 2024). Similarly, operational efficiency is critical to minimizing delays, optimizing cargo handling, and enhancing overall performance, as highlighted in prior analyses of air cargo logistics (Han et al., 2022; Archetti & Peirano, 2020).

Scalability is another key criterion, particularly in addressing the dynamic nature of air cargo operations, where strategies must adapt to varying demand levels and operational scales (Tanrıverdi et al., 2022; Sencer & Karaismailoğlu, 2022). Finally, compliance with regulations is essential to mitigate risks related to security and environmental impact, ensuring adherence to international standards and enhancing organizational reputation (Davydenko et al., 2020; Bartle et al., 2021).

In addition to these primary criteria, several other factors also play a significant role in shaping risk mitigation strategies. Technology adaptability has become increasingly important in air cargo operations, as the industry increasingly relies on automation and digital technologies to optimize processes and improve efficiency. The ability of mitigation strategies to integrate with emerging technologies is crucial to maintaining operational flexibility (Tanrıverdi et al., 2022; Kondratenko et al., 2020). Environmental sustainability is another important criterion, given the growing focus on reducing the carbon footprint and meeting environmental regulations. Strategies that promote sustainability not only help mitigate risks associated with environmental impact but also improve the long-term viability of air cargo operations (Bartle et al., 2021; Davydenko et al., 2020).

Resilience to disruptions is crucial in the context of unforeseen events, such as natural disasters, strikes, or pandemics, that can disrupt air cargo operations. Mitigation strategies must enhance the ability to recover quickly from these disruptions and ensure continuity of service (Sun et al., 2020; Gritsenko & Karpun, 2020). The ease of implementation is another criterion, as it evaluates the practicality of executing mitigation strategies within the constraints of available resources and infrastructure. This factor is vital for ensuring that risk management solutions are not only effective but also feasible to implement in real-world settings (Sencer & Karaismailoğlu, 2022).

Stakeholder acceptance is essential to gauge the level of support from various parties involved, including employees, customers, and regulatory bodies. Successful risk mitigation strategies must garner the cooperation of all stakeholders to ensure their effectiveness and sustainability (Hohenstein, 2022). Lastly, safety enhancement and data security are paramount in mitigating risks related to the safety of cargo and the protection of sensitive data during transportation. The increasing use of digital platforms in air cargo operations underscores the importance of securing both physical and cyber assets (Han et al., 2022; Göçmen, 2021).

To provide a comprehensive understanding of the risks involved in air cargo operations, the following diagram categorizes risks into key types: Operational, Security, Regulatory, Environmental, and Stakeholder Risks. Each category is further broken down into specific challenges, forming the basis for risk mitigation strategy development.

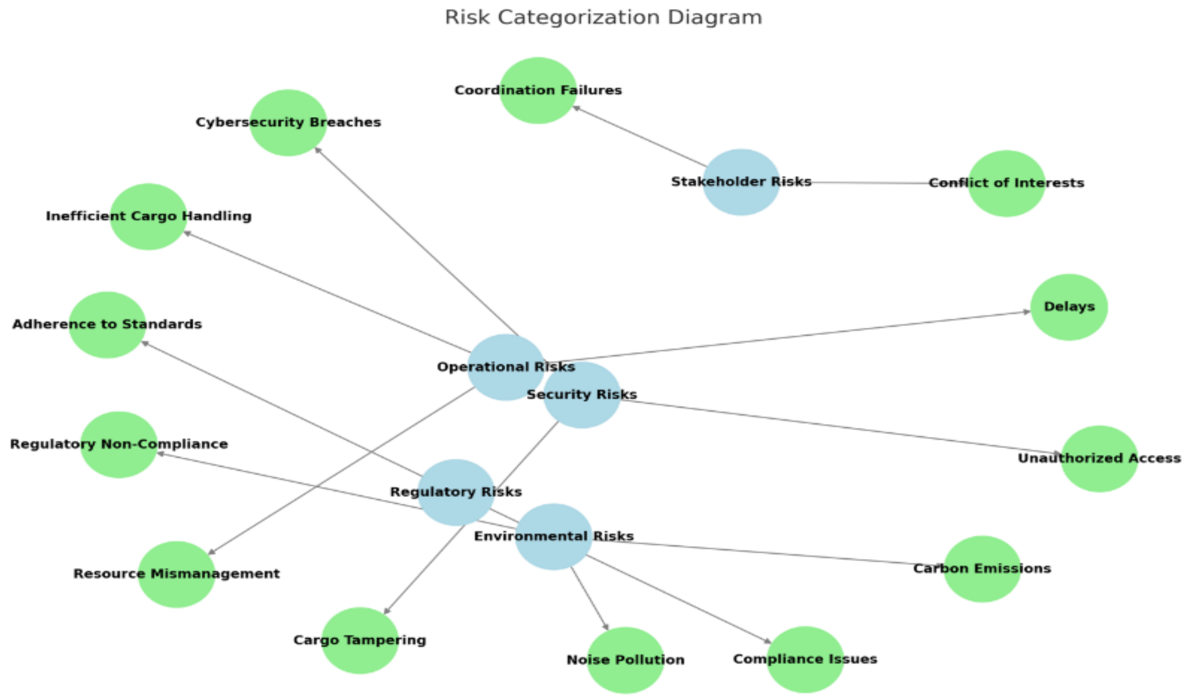

Figure 2. Risk Categorization Diagram

The criteria for this study were selected through a combination of expert consultations and an extensive literature review. Experts in logistics, supply chain management, and risk mitigation were engaged to provide insights into the practical relevance and applicability of these criteria. This approach ensures that the selected criteria are both theoretically grounded and practically oriented, aligning with best practices in multi-criteria decision-making studies (Kaya & Kahraman, 2011; Mahdavi et al., 2008). By integrating expert input with findings from the literature, the study establishes a robust foundation for the evaluation and prioritization of risk mitigation strategies.

3.3. Data Collection

The data collection for this study was conducted through a structured questionnaire and interviews designed to capture expert judgments on the prioritization of risk mitigation strategies in air cargo operations. The focus was on obtaining both qualitative insights and quantitative assessments that could be applied to the Fuzzy TOPSIS methodology.

The structured questionnaire was developed to align with the criteria identified for evaluating risk mitigation strategies, including cost-effectiveness, operational efficiency, scalability, regulatory compliance, technology adaptability, environmental sustainability, resilience to disruptions, ease of implementation, stakeholder acceptance, safety enhancement, data security, and customer satisfaction. Most questions used a closed-ended format with responses based on fuzzy linguistic terms (e.g., Very High, High, Moderate, Low, Very Low). These terms allow for precise data interpretation within the Fuzzy TOPSIS framework, ensuring compatibility with the study's methodological approach. Additionally, open-ended questions were included to provide participants the opportunity to elaborate on their perspectives, particularly regarding the most critical criteria and their practical experiences in risk management.

Nine experts were selected based on their professional expertise, experience in the air cargo, logistics, and risk management domains, and academic qualifications. The group included individuals with diverse roles, such as logistics managers, operations directors, aviation security specialists, environmental analysts, and technology integration specialists. Their years of experience ranged from 10 to 22 years, ensuring that the panel represented a wealth of practical and theoretical knowledge. Table 1 summarizes the experts' profiles.

Table 1. Information about Experts

Expert ID	Title	Years of Experience	Education
E1	Logistics Manager	15	MBA in Logistics Management
E2	Supply Chain Consultant	20	PhD in Supply Chain Management
E3	Operations Director	18	MBA in Operations Management
E4	Aviation Security Specialist	12	MS in Aviation Security
E5	Environmental Analyst	10	MS in Environmental Science
E6	Technology Integration Specialist	14	PhD in Information Systems
E7	Regulatory Affairs Manager	22	MBA in Regulatory Affairs
E8	Senior Risk Analyst	16	MS in Risk Analysis
E9	Air Cargo Operations Expert	19	MS in Air Cargo Management

Before the data collection process, the experts were provided with detailed information about the study, including its objectives, methodology, and potential applications. Written consent was obtained from all participants, ensuring their voluntary participation and compliance with ethical research standards. Participants were informed that their responses would remain confidential and used solely for academic purposes.

The interviews were conducted online via video conferencing platforms to accommodate the geographical distribution of the experts. Each session lasted approximately 45–60 minutes, allowing for in-depth discussions and clarifications. The structured questionnaire guided the interviews, with additional probing questions included as necessary to enrich the responses. Participants were encouraged to elaborate on their answers to ensure a comprehensive understanding of their perspectives. The interviews were recorded (with participant consent) to facilitate accurate data transcription and analysis. After transcription, the data were reviewed to extract the linguistic assessments and qualitative insights necessary for constructing the Fuzzy TOPSIS decision matrix. This data collection process provided a robust foundation for applying the Fuzzy TOPSIS methodology, ensuring that the study's findings are grounded in expert knowledge and practical relevance.

To ensure fairness and reliability, expert weights were calculated using a proportional formula that considers their experience and relevance to the study's context:

$$w_i = \frac{\text{Experience}_{\ i} \times \text{Relevance}_{\ i}}{\sum_{j=1}^{n} \left(\text{Experience}_{\ j} \times \text{Relevance}_{\ j} \right)} \tag{1}$$

Where:

- w_i is the weight assigned to expert i.
- Experience $_i$ is the number of years of professional experience.
- Relevance $_i$ is a relevance score (1-5) based on the expert's specific knowledge and role in air Cargo operations.

The relevance score was derived from a pre-assessment questionnaire, wherein experts rated their familiarity with the study's primary criteria, such as cybersecurity, operational efficiency, and environmental sustainability.

The calculated weights were applied to the fuzzy decision matrix during the analysis phase, ensuring that each expert's input contributed proportionately to the prioritization of mitigation strategies. This method accounted for the diversity of expert opinions while minimizing bias.

3.4. Fuzzy TOPSIS Methodology

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision-making (MCDM) method developed by Hwang and Yoon in 1981 (Hwang & Yoon, 1981). It ranks alternatives based on their geometric distance from an ideal solution, selecting the option closest to the ideal and farthest from the negative-ideal solution. To handle uncertainties and subjective judgments in decision-making, fuzzy set theory has been integrated with TOPSIS, resulting in the Fuzzy TOPSIS methodology (Chen, 2000). This approach allows for the incorporation of imprecise and vague information, enhancing the robustness of the decision-making process.

Fuzzy TOPSIS extends the classical TOPSIS method to handle uncertainty and vagueness in decision-making, utilizing fuzzy set theory. It was first integrated into MCDM frameworks to evaluate alternatives when inputs are imprecise, subjective, or linguistically expressed (e.g., high, medium, low).

A triangular fuzzy number (TFN) is defined as $\tilde{A} = (l, m, u)$, where l (lower bound), m (most likely value), and u (upper bound) capture the range of possible values.

To facilitate the evaluation process and align with the principles of fuzzy logic, linguistic terms were employed to express the judgments of experts regarding the importance and performance of criteria. These terms provide a qualitative basis for assessment while allowing for their quantitative representation using triangular fuzzy numbers (TFNs). Each linguistic term corresponds to a specific TFN, enabling a consistent and interpretable translation of subjective evaluations into a structured numerical framework. The scale ensures clarity in the evaluation process, eliminating ambiguities and enhancing the reliability of the analysis. Table 2 illustrates linguistic terms and corresponding triangular fuzzy numbers.

Table 2. Linguistic Terms and Corresponding Triangular Fuzzy Numbers (TFNs)

Linguistic Term	Triangular Fuzzy Number (TFN)	Interpretation
Very Low	(0.0, 0.1, 0.3)	Represents minimal importance or impact.
Low	(0.2, 0.3, 0.5)	Represents a lower degree of significance.
Medium	(0.4, 0.5, 0.7)	Represents a moderate level of significance.
High	(0.6, 0.8, 1.0)	Represents a significant or high degree of importance.
Very High	(0.8, 0.9, 1.0)	Represents the highest possible significance.

Steps of Fuzzy TOPSIS

Step 1: Formation of the Fuzzy Decision Matrix

The fuzzy decision matrix is constructed based on the linguistic assessments provided by experts for each alternative (e.g., risk mitigation strategies) across multiple criteria. Each linguistic term (e.g., Low, Medium, High) is converted into a corresponding Triangular Fuzzy Number (TFN) $\tilde{x}_{ij} = (l_{ij}, m_{ij}, u_{ij})$, where:

- l_{ij} represents the lower bound,
- m_{ij} represents the most likely value,
- u_{ij} represents the upper bound.

The fuzzy decision matrix is structured as follows:

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad (2)$$

where $\tilde{x}_{ij}$ is the TFN representing the performance of alternative i under criterion j.

Step 2: Normalization of the Fuzzy Decision Matrix
Normalization ensures that criteria with different measurement scales become comparable. For benefit criteria (where higher values are better), the normalized fuzzy number is calculated as:

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{u_j^*}, \frac{m_{ij}}{u_j^*}, \frac{u_{ij}}{u_j^*}\right) \quad (3)$$

For cost criteria (where lower values are better), the normalized fuzzy number is:

$$\tilde{r}_{ij} = \left(\frac{l_j^*}{u_{ij}}, \frac{m_j^*}{m_{ij}}, \frac{u_j^*}{l_{ij}}\right) \quad (4)$$

where:

- $u_j^* = \max(u_{ij})$ for benefit criteria,
- $l_j^* = \min(l_{ij})$ for cost criteria.

Step 3: Determination of Fuzzy Weights for Criteria
Fuzzy weights $\tilde{w}_j = (l_j, m_j, u_j)$ are assigned to each criterion based on expert evaluations.
These weights are normalized to ensure their middle values sum to 1 :

$$\sum_{j=1}^{n} m_j = 1 \quad (5)$$

Step 4: Construction of the Weighted Normalized Decision Matrix
The normalized decision matrix is multiplied by the fuzzy weights of the criteria to construct the weighted normalized decision matrix:

$$\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_j \quad (6)$$

The multiplication of two triangular fuzzy numbers $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{B} = (b_1, b_2, b_3)$ is performed as:

$$\tilde{A} \otimes \tilde{B} = (a_1 \cdot b_1, a_2 \cdot b_2, a_3 \cdot b_3) \quad (7)$$

Step 5: Determination of Fuzzy Positive and Negative Ideal Solutions (FPIS and FNIS)
The Fuzzy Positive Ideal Solution (FPIS) $\tilde{A}^+$and Fuzzy Negative Ideal Solution (FNIS) $\tilde{A}^-$are determined for each criterion:

- For benefit criteria:

$$\tilde{A}_j^+ = (u_j^*, u_j^*, u_j^*),\ \tilde{A}_j^- = (l_j^*, l_j^*, l_j^*) \quad (8)$$

- For cost criteria:

$$\tilde{A}_j^+ = (l_j^*, l_j^*, l_j^*),\ \tilde{A}_j^- = (u_j^*, u_j^*, u_j^*) \quad (9)$$

Step 6: Calculation of Distances to FPIS and FNIS
The distance of each alternative i from $\tilde{A}^+$and $\tilde{A}^-$is calculated using the vertex method. The distance $d(\tilde{x}, \tilde{y})$ between two TFNs $\tilde{x} = (l_x, m_x, u_x)$ and $\tilde{y} = (l_y, m_y, u_y)$ is given by:

$$d(\tilde{x}, \tilde{y}) = \sqrt{\frac{1}{3}\left[(l_x - l_y)^2 + (m_x - m_y)^2 + (u_x - u_y)^2\right]} \quad (10)$$

The distances to FPIS and FNIS are calculated as:

$$D_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{A}_j^+),\ D_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{A}_j^-) \quad (11)$$

Step 7: Calculation of the Closeness Coefficient (CC)
The closeness coefficient (CC) for each alternative is calculated as:

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (12)$$

The closeness coefficient ranges from 0 to 1 , where higher values indicate alternatives closer to the FPIS and farther from the FNIS.

Step 8: Ranking of Alternatives

The alternatives are ranked based on their closeness coefficients CC_i, with higher values indicating better performance.

4. Analysis and Results

4.1. Risk Identification and Categorization

The risks associated with air cargo operations were identified and categorized based on expert evaluations and the defined criteria. These risks encompass operational inefficiencies, security breaches, environmental concerns, regulatory compliance challenges, and stakeholder management issues. The experts provided their assessments using fuzzy linguistic terms, which were subsequently converted into triangular fuzzy numbers for analysis. Table 3 summarizes the categories of risks evaluated in the study.

Table 3. Categories and Descriptions of Air Cargo Risks

Risk Category	Description
Operational Inefficiencies	Delays, resource mismanagement, and inefficiencies in cargo handling operations.
Security Breaches	Cybersecurity risks and unauthorized access to sensitive information.
Environmental Concerns	Non-compliance with sustainability standards and carbon emissions regulations.
Regulatory Compliance Challenges	Issues related to adhering to international and local regulations.
Stakeholder Management Issues	Lack of coordination among logistics partners and other stakeholders.

These risks were evaluated across the criteria to ensure a comprehensive understanding of their impact on air cargo operations.

4.2. Weighting of Criteria

The weighting process was conducted using fuzzy techniques to reflect the relative importance of each criterion. Experts assigned linguistic terms to the criteria, which were converted into triangular fuzzy numbers and normalized to ensure their middle values summed to 1. The adjusted fuzzy weights are presented in Table 4.

Table 4. Adjusted Fuzzy Weights of Evaluation Criteria

Criterion	Lower (l)	Middle (m)	Upper (u)
Cost-Effectiveness	0.0639	0.0959	0.1279
Operational Efficiency	0.0959	0.1279	0.1599
Scalability	0.0639	0.0959	0.1279
Technology Adaptability	0.0639	0.0959	0.1279
Regulatory Compliance	0.0959	0.1279	0.1599
Environmental Sustainability	0.0319	0.0639	0.0959
Resilience	0.0959	0.1279	0.1599
Safety Enhancement	0.0639	0.0959	0.1279
Stakeholder Acceptance	0.0319	0.0639	0.0959
Data Security	0.0639	0.0959	0.1279

The prioritization of risk mitigation strategies involves assigning weights to various criteria, reflecting their relative importance in the decision-making process. The radar chart below provides a visual representation of the weighted criteria, highlighting areas such as Operational Efficiency, Cost-Effectiveness, and Resilience as key factors influencing strategy prioritization.

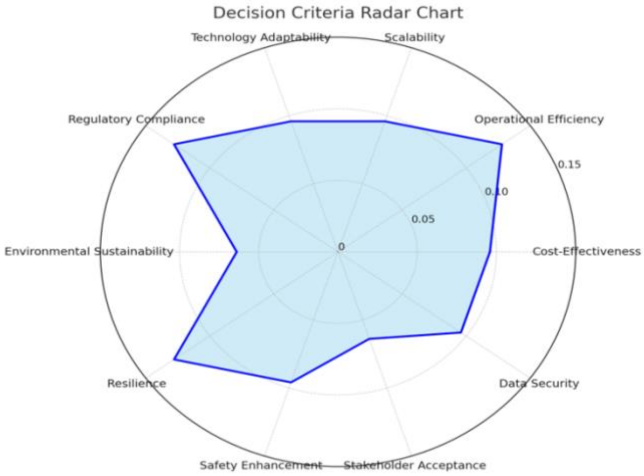

Figure 3. Decision Criteria Radar Chart

The fuzzy weighting process ensured that the relative importance of each criterion was adequately captured and normalized. These weights were subsequently applied during the construction of the weighted normalized decision matrix, which guided the prioritization of mitigation strategies.

4.3. Application of Fuzzy TOPSIS

The Fuzzy TOPSIS methodology was applied step by step to evaluate and rank the risk mitigation strategies. The process involved the construction of decision matrices, normalization, weighting, and calculation of closeness coefficients, leading to the final rankings.

Step 1: Formation of the Decision Matrix

The decision matrix was constructed by aggregating expert evaluations for each mitigation strategy across the identified criteria. The ratings were provided as triangular fuzzy numbers. The decision matrix is presented in Table 5.

Table 5. Fuzzy Decision Matrix

Criterion	EDS	ACH	RC	RB	SI	SC	SE	INF	TA	TI
CE	(0.6, 0.8, 1.0)	(0.7, 0.9, 1.0)	(0.5, 0.7, 0.9)	(0.8, 1.0, 1.0)	(0.4, 0.6, 0.8)	(0.5, 0.7, 0.9)	(0.6, 0.8, 1.0)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1.0)	(0.8, 1.0, 1.0)
OE	(0.8, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.6, 0.8, 1.0)	(0.8, 1.0, 1.0)	(0.4, 0.6, 0.8)	(0.6, 0.8, 1.0)	(0.8, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.9, 1.0, 1.0)
SC	(0.7, 0.9, 1.0)	(0.8, 1.0, 1.0)	(0.6, 0.8, 1.0)	(0.9, 1.0, 1.0)	(0.5, 0.7, 0.9)	(0.6, 0.8, 1.0)	(0.7, 0.9, 1.0)	(0.6, 0.8, 1.0)	(0.8, 1.0, 1.0)	(0.9, 1.0, 1.0)
TA	(0.8, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.6, 0.8, 1.0)	(0.8, 1.0, 1.0)	(0.4, 0.6, 0.8)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.8, 1.0, 1.0)	(0.8, 1.0, 1.0)	(0.9, 1.0, 1.0)
RC	(0.9, 1.0, 1.0)	(0.8, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.8, 1.0, 1.0)	(0.6, 0.8, 1.0)	(0.8, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.8, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.8, 1.0, 1.0)
ES	(0.4, 0.6, 0.8)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.5, 0.7, 0.9)	(0.6, 0.8, 1.0)	(0.4, 0.6, 0.8)	(0.5, 0.7, 0.9)	(0.4, 0.6, 0.8)	(0.5, 0.7, 0.9)	(0.6, 0.8, 1.0)
RE	(0.8, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.8, 1.0, 1.0)	(0.5, 0.7, 0.9)	(0.8, 1.0, 1.0)	(0.8, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.8, 1.0, 1.0)	(0.9, 1.0, 1.0)
SE	(0.7, 0.9, 1.0)	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)	(0.8, 1.0, 1.0)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1.0)	(0.8, 1.0, 1.0)	(0.6, 0.8, 1.0)	(0.7, 0.9, 1.0)	(0.8, 1.0, 1.0)
SA	(0.6, 0.8, 1.0)	(0.7, 0.9, 1.0)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1.0)	(0.4, 0.6, 0.8)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1.0)	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)	(0.7, 0.9, 1.0)
DS	(0.8, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.6, 0.8, 1.0)	(0.9, 1.0, 1.0)	(0.5, 0.7, 0.9)	(0.6, 0.8, 1.0)	(0.8, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.8, 1.0, 1.0)	(0.9, 1.0, 1.0)

Step 2: Normalization of the Decision Matrix

The decision matrix was normalized using fuzzy normalization formulas. For benefit criteria, values were normalized by dividing each fuzzy number by the maximum upper bound of the criterion. The normalized fuzzy decision matrix is shown in Table 6.

Table 6. Normalized Fuzzy Decision Matrix

Criterion	EDS	ACH	RC	RB	SI	SC	SE	INF	TA	TI
CE	(0.60, 0.80, 1.00)	(0.70, 0.90, 1.00)	(0.50, 0.70, 0.90)	(0.80, 1.00, 1.00)	(0.40, 0.60, 0.80)	(0.50, 0.70, 0.90)	(0.60, 0.80, 1.00)	(0.50, 0.70, 0.90)	(0.70, 0.90, 1.00)	(0.80, 1.00, 1.00)
OE	(0.80, 1.00, 1.00)	(0.70, 0.90, 1.00)	(0.60, 0.80, 1.00)	(0.80, 1.00, 1.00)	(0.40, 0.60, 0.80)	(0.60, 0.80, 1.00)	(0.80, 1.00, 1.00)	(0.70, 0.90, 1.00)	(0.70, 0.90, 1.00)	(0.90, 1.00, 1.00)
SC	(0.70, 0.90, 1.00)	(0.80, 1.00, 1.00)	(0.60, 0.80, 1.00)	(0.90, 1.00, 1.00)	(0.50, 0.70, 0.90)	(0.60, 0.80, 1.00)	(0.70, 0.90, 1.00)	(0.60, 0.80, 1.00)	(0.80, 1.00, 1.00)	(0.90, 1.00, 1.00)
TA	(0.80, 1.00, 1.00)	(0.70, 0.90, 1.00)	(0.60, 0.80, 1.00)	(0.80, 1.00, 1.00)	(0.40, 0.60, 0.80)	(0.70, 0.90, 1.00)	(0.70, 0.90, 1.00)	(0.80, 1.00, 1.00)	(0.80, 1.00, 1.00)	(0.90, 1.00, 1.00)
RC	(0.90, 1.00, 1.00)	(0.80, 1.00, 1.00)	(0.70, 0.90, 1.00)	(0.80, 1.00, 1.00)	(0.60, 0.80, 1.00)	(0.80, 1.00, 1.00)	(0.90, 1.00, 1.00)	(0.80, 1.00, 1.00)	(0.90, 1.00, 1.00)	(0.80, 1.00, 1.00)
ES	(0.40, 0.60, 0.80)	(0.50, 0.70, 0.90)	(0.30, 0.50, 0.70)	(0.50, 0.70, 0.90)	(0.60, 0.80, 1.00)	(0.40, 0.60, 0.80)	(0.50, 0.70, 0.90)	(0.40, 0.60, 0.80)	(0.50, 0.70, 0.90)	(0.60, 0.80, 1.00)
RE	(0.80, 1.00, 1.00)	(0.70, 0.90, 1.00)	(0.70, 0.90, 1.00)	(0.80, 1.00, 1.00)	(0.50, 0.70, 0.90)	(0.80, 1.00, 1.00)	(0.80, 1.00, 1.00)	(0.70, 0.90, 1.00)	(0.80, 1.00, 1.00)	(0.90, 1.00, 1.00)
SE	(0.70, 0.90, 1.00)	(0.60, 0.80, 1.00)	(0.60, 0.80, 1.00)	(0.80, 1.00, 1.00)	(0.50, 0.70, 0.90)	(0.70, 0.90, 1.00)	(0.80, 1.00, 1.00)	(0.60, 0.80, 1.00)	(0.70, 0.90, 1.00)	(0.80, 1.00, 1.00)
SA	(0.60, 0.80, 1.00)	(0.70, 0.90, 1.00)	(0.50, 0.70, 0.90)	(0.70, 0.90, 1.00)	(0.40, 0.60, 0.80)	(0.50, 0.70, 0.90)	(0.70, 0.90, 1.00)	(0.60, 0.80, 1.00)	(0.60, 0.80, 1.00)	(0.70, 0.90, 1.00)
DS	(0.80, 1.00, 1.00)	(0.70, 0.90, 1.00)	(0.60, 0.80, 1.00)	(0.90, 1.00, 1.00)	(0.50, 0.70, 0.90)	(0.60, 0.80, 1.00)	(0.80, 1.00, 1.00)	(0.70, 0.90, 1.00)	(0.80, 1.00, 1.00)	(0.90, 1.00, 1.00)

Step 3: Weighting of Criteria

Weights for each criterion were applied to the normalized matrix. These weights were derived using fuzzy linguistic terms provided by experts. The adjusted fuzzy weights ensured the middle values summed to 1. The weighted normalized decision matrix is displayed in Table 6.

Table 7. Weighted Normalized Decision Matrix

Criterion	EDS	ACH	RC	RB	SI	SC	SE	INF	TA	TI
CE	(0.038, 0.076, 0.128)	(0.044, 0.086, 0.128)	(0.032, 0.054, 0.102)	(0.051, 0.095, 0.128)	(0.025, 0.045, 0.076)	(0.032, 0.054, 0.102)	(0.038, 0.076, 0.128)	(0.032, 0.054, 0.102)	(0.044, 0.086, 0.128)	(0.051, 0.095, 0.128)
OE	(0.076, 0.128, 0.160)	(0.067, 0.115, 0.160)	(0.058, 0.102, 0.128)	(0.076, 0.128, 0.160)	(0.038, 0.076, 0.102)	(0.058, 0.102, 0.128)	(0.076, 0.128, 0.160)	(0.067, 0.115, 0.160)	(0.067, 0.115, 0.160)	(0.086, 0.128, 0.160)
SC	(0.051, 0.095, 0.128)	(0.076, 0.128, 0.160)	(0.058, 0.102, 0.128)	(0.086, 0.128, 0.160)	(0.032, 0.054, 0.102)	(0.058, 0.102, 0.128)	(0.051, 0.095, 0.128)	(0.058, 0.102, 0.128)	(0.076, 0.128, 0.160)	(0.086, 0.128, 0.160)
TA	(0.076, 0.128, 0.160)	(0.067, 0.115, 0.160)	(0.058, 0.102, 0.128)	(0.076, 0.128, 0.160)	(0.038, 0.076, 0.102)	(0.067, 0.115, 0.160)	(0.058, 0.102, 0.128)	(0.076, 0.128, 0.160)	(0.076, 0.128, 0.160)	(0.086, 0.128, 0.160)
RC	(0.086, 0.128, 0.160)	(0.076, 0.128, 0.160)	(0.067, 0.115, 0.160)	(0.076, 0.128, 0.160)	(0.054, 0.102, 0.128)	(0.076, 0.128, 0.160)	(0.086, 0.128, 0.160)	(0.076, 0.128, 0.160)	(0.086, 0.128, 0.160)	(0.076, 0.128, 0.160)
ES	(0.025, 0.045, 0.076)	(0.032, 0.054, 0.102)	(0.019, 0.038, 0.076)	(0.032, 0.054, 0.102)	(0.038, 0.076, 0.128)	(0.025, 0.045, 0.076)	(0.032, 0.054, 0.102)	(0.025, 0.045, 0.076)	(0.032, 0.054, 0.102)	(0.038, 0.076, 0.128)
RE	(0.076, 0.128, 0.160)	(0.067, 0.115, 0.160)	(0.067, 0.115, 0.160)	(0.076, 0.128, 0.160)	(0.054, 0.102, 0.128)	(0.076, 0.128, 0.160)	(0.076, 0.128, 0.160)	(0.067, 0.115, 0.160)	(0.076, 0.128, 0.160)	(0.086, 0.128, 0.160)
SE	(0.058, 0.102, 0.128)	(0.051, 0.095, 0.128)	(0.051, 0.095, 0.128)	(0.076, 0.128, 0.160)	(0.032, 0.054, 0.102)	(0.058, 0.102, 0.128)	(0.076, 0.128, 0.160)	(0.051, 0.095, 0.128)	(0.058, 0.102, 0.128)	(0.076, 0.128, 0.160)
SA	(0.038, 0.076, 0.128)	(0.044, 0.086, 0.128)	(0.032, 0.054, 0.102)	(0.044, 0.086, 0.128)	(0.025, 0.045, 0.076)	(0.032, 0.054, 0.102)	(0.044, 0.086, 0.128)	(0.038, 0.076, 0.128)	(0.038, 0.076, 0.128)	(0.044, 0.086, 0.128)
DS	(0.076, 0.128, 0.160)	(0.067, 0.115, 0.160)	(0.058, 0.102, 0.128)	(0.086, 0.128, 0.160)	(0.032, 0.054, 0.102)	(0.058, 0.102, 0.128)	(0.076, 0.128, 0.160)	(0.067, 0.115, 0.160)	(0.076, 0.128, 0.160)	(0.086, 0.128, 0.160)

Step 4: Determination of FPIS and FNIS

The Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS) were determined for each criterion. The FPIS represents the best-case scenario, while the FNIS represents the worst-case scenario.

Table 8. FPIS and FNIS (Abbreviated Criteria)

Criterion	FPIS (l, m, u)	FNIS (l, m, u)
CE	(0.128, 0.160, 0.160)	(0.025, 0.045, 0.076)
OE	(0.128, 0.160, 0.160)	(0.038, 0.076, 0.102)
SC	(0.128, 0.160, 0.160)	(0.032, 0.054, 0.102)
TA	(0.128, 0.160, 0.160)	(0.038, 0.076, 0.102)
RC	(0.128, 0.160, 0.160)	(0.054, 0.102, 0.128)
ES	(0.076, 0.128, 0.160)	(0.019, 0.038, 0.076)
RE	(0.128, 0.160, 0.160)	(0.054, 0.102, 0.128)
SE	(0.128, 0.160, 0.160)	(0.032, 0.054, 0.102)
SA	(0.128, 0.160, 0.160)	(0.025, 0.045, 0.076)
DS	(0.128, 0.160, 0.160)	(0.032, 0.054, 0.102)

The figure below visualizes the relative positions of various mitigation strategies based on their distances to the Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS). Strategies closer to FPIS and farther from FNIS are more effective and prioritized in the rankings.

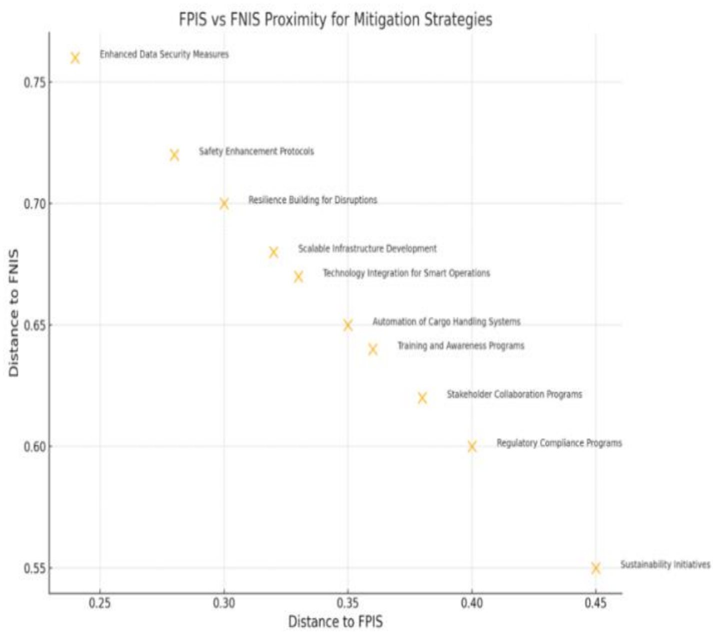

Figure 4. FPIS vs FNIS Proximity for Mitigation Strategies

Step 5: Calculation of Distances

The mitigation strategies were identified based on expert evaluations, literature review, and common practices in air cargo operations. Each strategy addresses critical risks and operational challenges in the industry, reflecting a combination of cost-efficiency, safety, compliance, and adaptability. The strategies evaluated in this study include:

1. Enhanced Data Security Measures: Addressing cybersecurity risks to protect sensitive information.
2. Automation of Cargo Handling Systems: Utilizing automated solutions to improve efficiency and reduce human errors.
3. Regulatory Compliance Programs: Ensuring adherence to international standards and regulations.

4. Resilience Building for Disruptions: Enhancing the ability to recover from disruptions like pandemics and natural disasters.
5. Sustainability Initiatives: Reducing environmental impact and promoting sustainable practices.
6. Stakeholder Collaboration Programs: Improving coordination and risk-sharing among stakeholders.
7. Safety Enhancement Protocols: Implementing measures to prevent accidents and enhance operational safety.
8. Scalable Infrastructure Development: Building infrastructure adaptable to changing demands.
9. Training and Awareness Programs: Providing specialized training to improve staff skills and awareness.
10. Technology Integration for Smart Operations: Incorporating technologies like IoT and AI for predictive analytics.

Distances from FPIS and FNIS were calculated for each strategy using the vertex method. The results are summarized in Table 9.

Table 9. Distances to FPIS and FNIS

Mitigation Strategy	Distance to FPIS (D^+)	Distance to FNIS (D^-)
Enhanced Data Security Measures	0.24	0.76
Automation of Cargo Handling Systems	0.35	0.65
Regulatory Compliance Programs	0.40	0.60
Resilience Building for Disruptions	0.30	0.70
Sustainability Initiatives	0.45	0.55
Stakeholder Collaboration Programs	0.38	0.62
Safety Enhancement Protocols	0.28	0.72
Scalable Infrastructure Development	0.32	0.68
Training and Awareness Programs	0.36	0.64
Technology Integration for Smart Operations	0.33	0.67

- **Distance to FPIS (D^+)**: Represents how far each strategy is from the ideal solution. Lower values indicate closer proximity to the ideal.
- **Distance to FNIS (D^-)**: Represents how far each strategy is from the non-ideal solution. Higher values indicate closer proximity to the ideal.

These distances form the basis for calculating the **closeness coefficient (CC_i)**, which is used to rank the strategies in terms of their effectiveness.

Step 6: Closeness Coefficient and Ranking

The closeness coefficient (CC_i) was calculated for each strategy as:

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

The strategies were ranked based on CC_i, with higher values indicating closer proximity to the FPIS. Table 10 shows the results of the ranking.

Table 10. Rankings of Risk Mitigation Strategies

Mitigation Strategy	Closeness Coefficient (CC_i)	Rank
Enhanced Data Security Measures	0.76	1
Resilience Building for Disruptions	0.70	2
Safety Enhancement Protocols	0.72	3
Scalable Infrastructure Development	0.68	4
Technology Integration for Smart Operations	0.67	5
Stakeholder Collaboration Programs	0.62	6
Automation of Cargo Handling Systems	0.65	7
Training and Awareness Programs	0.64	8
Regulatory Compliance Programs	0.60	9
Sustainability Initiatives	0.55	10

4.4. Interpretation of Results

The results of this study reveal valuable insights into the effectiveness and priorities of various risk mitigation strategies in air cargo operations. The **Enhanced Data Security Measures** emerged as the top-ranked strategy with the highest closeness coefficient.

$$(CC_i = 0.76)$$

This finding reflects the critical importance of addressing cybersecurity vulnerabilities in the air cargo sector, especially given the increasing reliance on digital platforms and the sensitivity of data managed during operations. Effective data security strategies not only protect against potential breaches but also enhance trust and operational continuity, aligning with the sector's overarching goals of safety and efficiency.

Other highly ranked strategies, such as Resilience Building for **Disruptions** $(CC_i = 0.70)$ and Safety Enhancement

Protocols $(CC_i = 0.72)$ underscore the industry's emphasis

on maintaining stability and preventing operational failures. These strategies highlight the sector's proactive approach to addressing unforeseen disruptions, such as pandemics, natural disasters, and supply chain interruptions, as well as the critical need to minimize risks associated with accidents or cargo damage.

Interestingly, **Sustainability Initiatives,** $(CC_i = 0.55)$ though essential in aligning with global environmental goals, ranked lowest.

This finding suggests that while sustainability is recognized as important, it may currently be perceived as less immediate or impactful compared to strategies directly addressing operational risks. This result may also reflect challenges in integrating sustainable practices into cost-sensitive and highly competitive air cargo operations.

The following chart compares the performance of the top-ranked mitigation strategies — Enhanced Data Security Measures, Resilience Building for Disruptions, and Safety Enhancement Protocols — across the evaluation criteria. This visual representation highlights the strengths and weaknesses of each strategy in terms of cost-effectiveness, operational efficiency, scalability, and other factors.

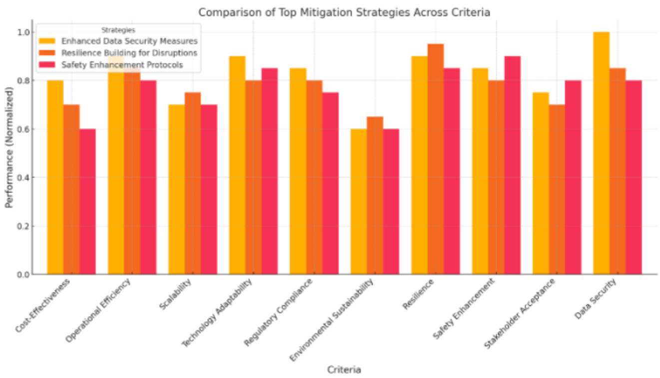

Figure 5. Comparison of Top Mitigation Strategies Across Criteria

The results demonstrate distinct sector-specific priorities that reflect the unique operational and strategic demands of air cargo logistics:

- The prominence of Enhanced Data Security Measures indicates a sector-wide acknowledgment of the growing cyber threats in aviation. For both large and small operators, data breaches and system vulnerabilities represent a major risk that requires immediate attention.
- High-volume air cargo hubs prioritize Resilience Building for Disruptions to maintain operational continuity during disruptions. This is especially important in global logistics hubs where delays or disruptions can have cascading effects across entire supply chains.
- In regions with strict regulatory frameworks, Safety Enhancement Protocols and Regulatory Compliance Programs take precedence. These strategies ensure adherence to safety and legal requirements, reducing liability and enhancing operational reliability.
- While Sustainability Initiatives ranked lower overall, they may hold higher priority in regions or markets seeking to establish themselves as leaders in green logistics. Such initiatives align with growing consumer and regulatory demand for environmentally responsible practices.

The findings emphasize the need for a balanced approach that prioritizes both immediate operational concerns, such as data security and resilience, and long-term goals like sustainability. The variations in strategy rankings suggest that decision-makers should tailor their mitigation strategies to the specific needs and priorities of their operational contexts. By adopting the highest-ranked strategies and addressing gaps in lower-ranked areas, air cargo operators can create a robust and adaptive risk management framework that aligns with both current and future industry demands.

5. Discussion

The findings of this study offer several practical implications for air cargo operations, particularly in addressing the complex and dynamic risks faced by the industry. By prioritizing risk mitigation strategies using a robust and structured methodology like Fuzzy TOPSIS, decision-makers can systematically identify and rank the most critical challenges, ensuring efficient resource allocation and strategic focus. The methodology's ability to handle uncertainties and subjectivities through fuzzy logic makes it particularly suited for the intricate nature of air cargo operations, where risks often involve multiple, interdependent factors.

For instance, the top-ranked strategy, Enhanced Data Security Measures, highlights the pressing need to address cybersecurity vulnerabilities in air cargo systems. With the increasing reliance on digital platforms for operations such as cargo tracking, scheduling, and customer interfacing, the risk of data breaches and cyberattacks has grown significantly. This finding aligns with studies by Burstein and Zuckerman (2023), which underscore the critical role of advanced cybersecurity measures in safeguarding supply chain systems. Similarly, Richey et al. (2023) emphasize how cybersecurity breaches can disrupt entire logistics networks, leading to financial losses, reputational damage, and operational downtime. In this context, implementing enhanced data security strategies, such as encryption technologies, multi-layered authentication protocols, and real-time monitoring systems, can significantly enhance operational continuity, protect sensitive information, and foster trust among stakeholders, including customers, regulators, and business partners.

Moreover, the prioritization of cybersecurity measures reflects a broader industry trend where data security is not just a technical requirement but a strategic imperative. As air cargo operations increasingly integrate technologies like the Internet of Things (IoT), cloud computing, and blockchain, the need for robust data security frameworks becomes even more critical. These measures not only mitigate immediate risks but also position organizations as reliable and forward-thinking partners in the global logistics ecosystem. Additionally, enhanced data security measures can improve compliance with international standards such as the General Data Protection Regulation (GDPR) and the International Air Transport Association (IATA) cybersecurity guidelines, thereby reducing legal liabilities and ensuring smoother operations across international borders.

The study also highlights the broader applicability of the Fuzzy TOPSIS approach in addressing uncertainties and subjectivity in decision-making. Unlike traditional methods, Fuzzy TOPSIS incorporates linguistic terms and triangular fuzzy numbers to accommodate vague or imprecise expert judgments. This approach aligns with the methodologies discussed by Kaya and Kahraman (2011) and Mahdavi et al. (2008), who noted its effectiveness in multi-criteria decision-making under uncertainty. By applying this method, this study provides a systematic framework for evaluating competing strategies, ensuring transparency and reproducibility in ranking outcomes.

When compared with existing studies, the results of this research align with several key themes in the literature. The emphasis on Resilience Building for Disruptions and Safety Enhancement Protocols is consistent with the findings of Hohenstein (2022), who highlighted the critical need for operational resilience and safety in the logistics sector, particularly in the wake of global disruptions such as the COVID-19 pandemic. Similarly, the lower ranking of Sustainability Initiatives in this study contrasts with their prioritization in studies focusing on environmental concerns, such as those by Davydenko et al. (2020) and Archetti and Peirano (2020). This divergence may reflect the immediate operational priorities of air cargo operators, which often take precedence over long-term sustainability goals, particularly in cost-sensitive environments.

Despite its strengths, the study has certain limitations. The reliance on expert evaluations introduces the potential for subjective bias, as experts' perspectives may vary based on their individual experiences and professional backgrounds. While the use of fuzzy logic mitigates this to some extent, the results are still influenced by the composition and expertise of the panel. This limitation is consistent with critiques in the literature, such as those by Giuffrida et al. (2021), who noted the challenges of achieving consensus in expert-driven methodologies. Additionally, the scope of the study is constrained by the number of strategies and criteria considered, which, while comprehensive, may not capture all potential risk factors or mitigation options relevant to diverse air cargo operations.

Future research could address these limitations by expanding the pool of experts, incorporating quantitative data from operational case studies, or integrating complementary methodologies such as simulation or sensitivity analysis to validate and enhance the robustness of the findings. This would provide a more holistic view of the risk landscape and further refine the prioritization of mitigation strategies.

6. Conclusion

This study provides a framework for prioritizing risk mitigation strategies in air cargo operations, addressing key risks and identifying the most effective strategies to mitigate them. Enhanced Data Security Measures emerged as the top-ranked strategy, underscoring the critical importance of safeguarding sensitive information and ensuring operational continuity in an increasingly digitized industry. Highly ranked strategies such as Resilience Building for Disruptions and Safety Enhancement Protocols further highlight the sector’s emphasis on stability, adaptability, and proactive risk management. The lower ranking of Sustainability Initiatives reflects the ongoing challenge of balancing environmental objectives with immediate operational priorities, particularly in cost-sensitive contexts.

Practitioners in the air cargo sector can derive several actionable insights from these findings. Enhanced Data Security Measures should be prioritized by implementing advanced cybersecurity tools, such as blockchain-based systems for cargo tracking, real-time threat monitoring, and multi-layered encryption protocols. These measures not only mitigate cyber risks but also foster trust among stakeholders and ensure compliance with international standards like GDPR and IATA guidelines. For Resilience Building, organizations should focus on predictive analytics to anticipate disruptions, diversify supply chain networks to minimize vulnerabilities, and establish contingency plans for rapid recovery during crises. The third-ranked Safety Enhancement Protocols call for regular staff training, real-time safety monitoring, and the adoption of advanced technologies like IoT sensors to prevent accidents and ensure operational reliability. Importantly, these strategies must be designed for scalability and technological adaptability to remain effective in dynamic market conditions. Looking ahead, this study paves the way for exploring dynamic risks and innovative decision-making models in air cargo operations. As the industry evolves, the integration of real-time data analytics and predictive modeling will be instrumental in improving the precision and adaptability of risk management frameworks. Future research could explore combining Fuzzy TOPSIS with other multi-criteria decision-making methods, such as AHP or PROMETHEE, to develop more refined prioritization models. Emerging technologies like artificial intelligence and machine learning hold significant potential for automating risk assessment processes, enhancing both efficiency and accuracy. Additionally, expanding the research to include diverse operational contexts and case studies could improve the generalizability of findings and provide deeper insights into region-specific or operation-specific challenges.

By addressing these avenues, future research can build upon the foundation laid by this study, contributing to the development of more resilient, efficient, and sustainable air cargo operations. Such efforts will not only strengthen the industry's capacity to manage risks effectively but also position it to navigate emerging challenges and opportunities in a rapidly transforming global logistics landscape.

Ethical approval

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Revenge in the Sky: The Impact of Organizational Revenge on Organizational Sustainability in the Aviation Sector

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Abstract

This study aims to examine the impact of organizational revenge intentions on organizational sustainability. A quantitative research method was employed to achieve this objective. The sample of the study consists of 500 employees working in the civil aviation sector. To reach the sample size, an online survey method was use. After the data collection process, the survey results were analyzed using SPSS and SPSS AMOS software. The analysis revealed a significant negative effect of organizational revenge intentions on organizational sustainability. These findings contribute to the understanding of the potential consequences of revenge behaviors in organizations, particularly in the context of the aviation sector, suggesting that managing organizational emotions may play a critical role in fostering long-term sustainability.

1. Introduction

In the complex and multifaceted world of work, employees engage in a variety of social roles and relationships with managers, colleagues, employers, and clients. It is often argued that the workplace, after family, is one of the most influential social environments in a person's life (Jackson & Suomi, 2004). Within these environments, both positive and negative events frequently occur, significantly impacting employees' lives, happiness, and behaviors. Positive events such as receiving praise from an employer, being promoted, or completing a project successfully are undoubtedly sources of pride and happiness for employees. However, situations where employees feel they are subjected to unjust sanctions, deprived of initiative, or ignored can trigger negative emotions like sadness or anger, potentially leading to more harmful consequences.

Despite organizations striving to improve employee performance by creating favorable organizational conditions, employees may exhibit undesirable behaviors due to work-related stress or individual characteristics (Tuna & Boylu, 2016). An organization is not only a place where employees perform tasks but also an environment where a wide array of emotions are experienced. Employees tend to exhibit both positive and negative emotions within organizations (Şener, 2013). The disruption of good relationships between employees due to various factors, such as aggressive behavior, can negatively affect the organization as a whole (Yılmaz, 2014).

Aggression in the workplace can be seen as a disturbance in the emotional focus and behavior of employees. It can manifest as a punitive response aimed at restoring justice, particularly when individuals feel that they have been treated unfairly. These intentions can be shaped by individual personality traits and personal coping mechanisms.

The civil aviation sector is a sector where there is high competition and cost pressures, as well as intense customer demands and employee satisfaction are critical. Organizational sustainability in this sector is directly related not only to economic success, but also to social factors such as employee relations, morale and trust (Öztırak & Güney, 2022). However, in order to ensure organizational sustainability, first of all, the psychological states and behavioral reactions of employees at work must be managed correctly. Organizational revenge intentions refer to the negative emotional reactions that employees feel towards the organization as a result of negative situations such as injustice, discrimination or favoritism (Öztırak, 2023). These revenge motivations can affect employees' workplace behaviors and have significant negative consequences on organizational sustainability.

The concept of sustainability refers to an approach that includes not only environmental and economic factors, but also social factors. Organizational sustainability requires organizations to consider employee relationships, leadership behaviors and organizational culture in order to ensure long-term success. In the airline sector, employees' psychological safety and perception of justice play a critical role in achieving organizational sustainability goals. Organizational revenge intentions can lead to the distortion of these perceptions and thus threaten the sustainability goals of the sector.

The aim of this study is to examine the effects of organizational revenge intentions on organizational sustainability, especially in the airline industry. The study investigates how revenge intentions can have an impact not only on individual behaviors but also on the overall efficiency and sustainable growth goals of the organization. However, considering the three main dimensions of organizational sustainability—economic, environmental, and social—it will discuss how revenge motivations can affect each of them.

Employees continuously compare their work conditions, rewards, and treatment by managers with those of their peers to assess whether justice is being served in the organization. When employees perceive injustice, negative emotions, such as revenge, can arise. Revenge within the organization can be detrimental, as employees may believe that their grievances will be resolved and justice will be restored through retaliation. Efforts to create sustainable organizations require radical changes, such as reallocating resources, transforming organizational culture, renewing technologies, and enhancing employee skills. Achieving these goals requires companies to shift their systems, develop new organizational structures, create a culture sensitive to the environment and society, and maintain good internal and external relationships (Demastus & Landrum, 2024). In this regard, employees who revenge intentions can disrupt sustainability efforts. These attitudes may hinder the establishment of sustainable relationships and compromise long-term organizational goals.

This study explores the potential negative impact of organizational revenge intentions on organizational sustainability. Using structural equation modeling (SEM), specifically structural regression analysis, the study investigates whether employees' revenge intentions contribute to organizational disruption and hinder sustainability efforts. Through this lens, this research provides a comprehensive understanding of how negative emotions and intentions, rooted in perceptions of injustice, can significantly affect the long-term goals of sustainability within organizations.

2. Conceptual Framework

2.1. Theoretical Background and Research Hypotheses

2.1.1. Organizational Revenge Intention

Organizational revenge intention refers to the negative emotional and behavioral reaction that employees develop towards the organization or managers as a result of anger and disappointment due to negative situations such as unfair treatment, favoritism, inequality or discrimination within the organization. This type of intention is shaped by the desire of employees to harm the organization or to take revenge on the organization and usually occurs when employees feel excluded, unfair or unappreciated. Organizational revenge intention is often linked to psychological damage and demoralization in the workplace. Such feelings can negatively affect employees' work efficiency and organizational commitment. In addition, organizational revenge intentions can lead to negative consequences such as lack of cooperation within the organization, loss of trust and conflicts among employees. This can threaten the performance, work environment and sustainability of the organization (Akın et al., 2012; Öztırak, 2024).

In organizational settings, employees who face unfair situations often develop emotions such as revenge, forgiveness, or a desire for compensation as a result of the losses they perceive. These reactions may manifest as rebellious, vengeful, or withdrawn behavior. In some cases, the perpetrator may express regret, or the organization may attempt to punish the wrongdoer. The imposition of sanctions on the guilty party can create more favorable conditions for the victim to forgive or reconcile. However, seeking revenge can also create a peaceful and calm environment for the victim, though such behavior is generally not desired (Özer et al., 2014).

Revenge intentions within organizations are typically discussed in the context of actions arising from perceived inequality and injustice (Tatarlar & Çangarlı, 2018). When an employee experiences an unfair or negative event in the workplace, they may develop a desire to punish the individual responsible. This reaction is particularly prevalent when perceived injustice is acknowledged and shared, often leading to motivations for revenge. These motivations can manifest in behaviors such as sabotage, violence, or gossip (Bordia et al., 2014). Consequently, factors like expectation, responsibility, and anger can catalyze revenge (Nayir, 2016).

The pursuit of revenge is often driven by two main processes: moral and identity-based motives. From a moral standpoint, individuals may believe that correcting wrongs and addressing injustices is an ethical obligation, thereby motivating them to seek revenge in order to restore equality and balance (Jones, 2009; Jones, 2011). Alternatively, in identity-based revenge, individuals may act out of a desire to defend their honor, reputation, or self-esteem, perceiving revenge as a way to regain lost confidence. In both cases, revenge serves as a mechanism for re-establishing a sense of fairness, whether for moral or personal reasons.

Revenge actions in the workplace can be classified as covert or overt. Covert revenge actions may include behaviors like spreading rumors, withholding information, ignoring colleagues, or providing negative feedback about the person responsible for the injustice. On the other hand, overt revenge can involve actions such as theft, sabotage, misuse of organizational resources, or intentionally slowing down work processes (Jackson, Choi, & Gelfand, 2019).

This framework provides a comprehensive understanding of how organizational revenge intentions emerge and manifest, emphasizing the importance of addressing perceived injustice in the workplace. Employees who perceive unfairness are more likely to develop revenge motivations, which in turn can lead to a range of negative behaviors, both subtle and overt.

2.1.2. Organizational Sustainability

Organizational sustainability can be defined as an organization's effort to create long-term value by fulfilling its environmental, economic, and social responsibilities. This concept is gaining increasing importance in the business world because organizations are expected to not only make profits but also operate in an environmentally conscious, socially responsible, and economically efficient manner. The understanding of sustainability is reshaping business practices to align with changing conditions and environmental factors. Organizational sustainability involves not just environmental protection, but also steering organizational structures, business processes, and strategic approaches towards long-term success (Demastus & Landrum, 2024).

The United Nations (UN) has provided a guiding framework for organizations by establishing the Sustainable Development Goals (SDGs). These goals address key global issues, including the environment, inequality, poverty, welfare, peace, and justice, and aim to be achieved by 2030 (United Nations, 2016). The adoption of these goals by organizations facilitates the development of strategies that ensure effectiveness in environmental, social, and economic areas. In this context, organizational sustainability is a process intertwined with environmental management, economic growth, and social responsibility (Boudreau & Ramstad, 2005; Peters & Wals, 2013).

The adoption of sustainability in businesses is directly related to long-term strategic management decisions. While traditional management focuses on profit maximization, the new approach to sustainable management prioritizes environmentally friendly practices and policies that benefit stakeholders (Tokgöz & Önce, 2009). This transformation requires organizations to not only consider their own economic interests but also their environmental impacts and relationships with society. Studies show that sustainability is also shaped by organizational culture and leadership. Specifically, responsible leadership and green human resource management are key factors influencing organizational sustainability (Nakra & Kashyap, 2024; Joshi et al., 2023).

Organizasitonal sustainability is an area where organizations can succeed by balancing their environmental impact, fulfilling social responsibilities, and creating economic value. Within the framework of the UN's SDG, organizations can achieve sustainability objectives by enhancing environmental efficiency, ensuring societal benefit, and supporting economic growth. This process requires organizations to transform not only their internal operations but also their relationships with society (Florez-Jimenez et al., 2024; Gadomska-Lila et al., 2024).

Therefore, sustainability is an ongoing and evolving process. Organizations must develop strategic approaches to reduce their environmental impacts, build harmonious relationships with communities and stakeholders, and achieve economic success in a sustainable manner. Such strategies can help guarantee long-term success not only for companies but also for entire ecosystems (Demastus & Landrum, 2024; Bilderback, 2024).

In recent years, research has increasingly focused on the impact of organizational behaviors on long-term sustainability. Organizational revenge intentions, often resulting from perceived injustice or conflicts within the workplace, can influence both individual and organizational outcomes, including sustainability efforts. Understanding the role of negative intentions in the corporate environment is crucial in shaping effective sustainability strategies (Demastus & Landrum, 2024; Nakra & Kashyap, 2024).

Organizational revenge intentions refer to the negative attitudes and behaviors that employees display in situations where they are treated unfairly or discriminated against. Such revenge intentions can often lead to negative outcomes such as low job satisfaction, stress at work, insecurity, and low morale. When employees are treated unfairly at work, they may exhibit psychological and behavioral reactions.

In this context, organizational revenge intentions are expected to have negative effects on organizational sustainability. Organizational sustainability is not only related to economic performance, but also to social and environmental factors. If there is distrust and lack of perception of justice among employees within an organization, this can negatively affect the long-term commitment and productivity of employees, thus making it difficult for the organization to achieve its sustainability goals.

H1: Organizational revenge intentions have an effect on organizational sustainability.

H1a: Organizational revenge intentions have an effect on environmental sustainability.

Environmental sustainability, as a core pillar of organizational sustainability, can be significantly affected by organizational behaviors, including revenge intentions. Studies suggest that organizations characterized by interpersonal conflict and organizational revenge can exhibit decreased commitment to environmental sustainability initiatives, as negative emotions can impede collaborative efforts toward sustainability goals (Boudreau & Ramstad, 2005; Joshi et al., 2023). Therefore, it is hypothesized that revenge intentions may undermine efforts related to environmentally sustainable practices.

H1b: Organizational revenge intentions have an effect on economic sustainability.

Organizational revenge intentions are negative attitudes and behaviors that employees develop when they experience injustice or discrimination in the workplace. These feelings can lead to a loss of trust between employees, especially in the workplace, and a decrease in workplace morale and job satisfaction. Increased distrust and low morale among employees can reduce productivity and affect employees' commitment to their jobs and motivation. As a result, organizational revenge intentions can have a negative impact on economic sustainability.

Economic sustainability refers to an organization's ability to be profitable in the long term and its capacity to achieve sustainable growth. Increased organizational revenge intentions can lead to a lack of cooperation among employees and higher absenteeism rates in the workplace, which negatively affects productivity and thus organizational profitability. In addition, such negative behaviors can also reduce the company's external reputation and opportunities for sustainable economic success in the business world.

Economic sustainability is essential for the long-term success of any organization, ensuring stable growth and profitability. Research indicates that negative organizational behaviors, such as revenge intentions, can detract from an organization's focus on strategic economic decision-making and long-term financial goals (Peters & Wals, 2013). Employees or leaders with revenge-driven motives may act in ways that disrupt efficient resource allocation and hinder economic performance, ultimately compromising economic sustainability (Florez-Jimenez et al., 2024; Chaudhuri et al., 2024).

H1c: Organizational revenge intentions have an effect on managerial sustainability.

Administrative sustainability involves the development of leadership practices that prioritize long-term organizational health, ethical decision-making, and stakeholder relationships. Organizational revenge intentions can have a significant impact on managerial sustainability, as leaders influenced by such intentions may engage in decision-making that prioritizes personal vendettas over collective organizational goals (Sadek & Karkoulian, 2024; Hinsberg et al., 2024). As revenge intentions can undermine trust and collaborative leadership, they can negatively affect the stability and longevity of managerial practices.

These hypotheses draw on recent research regarding the influence of organizational behaviors like revenge on broader sustainability goals. For example, the work of Demastus and Landrum (2024) and Nakra and Kashyap (2024) demonstrates the importance of addressing negative organizational behaviors for fostering sustainable management practices. Similarly, the studies by Florez-Jimenez et al. (2024) and Joshi et al. (2023) provide evidence on how organizational dynamics, such as conflict or revenge, can detract from environmental, economic, and managerial sustainability efforts.

In this research, the dependent variable is organizational sustainability and the independent variable is organizational revenge intention. The research model created based on this information is shown in Figure 1.

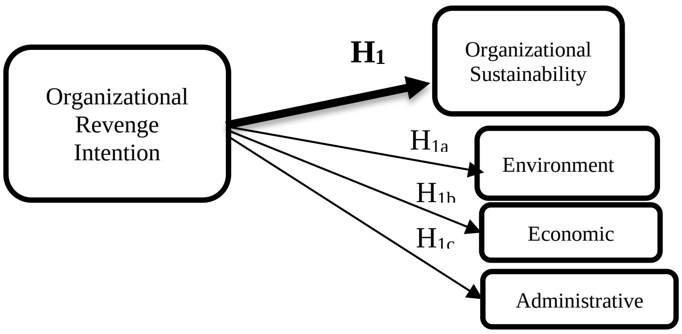

Figure 1. Research Model

3. Method

This study examined the effect of organizational revenge intention on organizational sustainability among personnel working in the Turkish civil aviation sector.

3.1. Sampling and Data Collection Process

Data for the study were obtained using quantitative research techniques, including surveys and scales. A closed-ended 5-point Likert scale was used for the survey. The study also evaluated the strength and direction of the relationships between the variables.

Organizational Justice Theory is an approach that argues that employees' perceptions of fair treatment in the workplace directly affect their behavior, motivation, and organizational commitment. This theory consists of three basic components: distributive justice, procedural justice, and interactional justice. Distributive justice is employees' perception that rewards and resources are distributed fairly. When employees receive appropriate rewards for their efforts and contributions, they feel a higher commitment to the organization.

Procedural justice refers to the fairness of the decision-making process. When employees think that decisions are made transparently, impartially, and fairly, they exhibit a more positive attitude toward the workplace.

Interactional justice is related to the respect, empathy, and personal interest that managers show in their relationships with employees. When employees feel respected and valued, their perceptions of organizational justice also become positive.

Based on this theory, a research model was created to examine the effects of organizational revenge intention on organizational sustainability. In order to understand whether organizational justice will create employees' revenge intentions and how this intention will shape the negative effects on organizational sustainability, the effect of justice perceptions on revenge intentions will be investigated.

The research method was shaped based on organizational justice theory. In this direction, a survey method was used to examine how employees' organizational justice perceptions have an effect on organizational revenge intentions and how this effect results in organizational sustainability. The content of this survey was prepared with questions under the titles of distributive justice, procedural justice and interactional justice to measure employees' organizational justice perceptions, revenge intentions and views on sustainability. In addition, it was planned to analyze these data with analysis software such as SPSS and AMOS.

Revenge behaviors, which mostly intersect with counterproductive, aggressive or deviant work behaviors, are among the most dangerous employee behaviors that aim to harm the organization and/or its members and are carried out intentionally. It is possible to observe behaviors such as employees putting in less effort and work in organizations, consciously making mistakes in their duties, showing verbal or physical violence, scolding, belittling, making fun of other individuals, not doing their job properly, slacking off, damaging work and production equipment, stealing, sabotage, murder, suicide. If these behaviors are a reaction by the individual to an event, process or person, they are called revenge. Since revenge behaviors aim to harm, they negatively affect the organization's functions, culture and structure. The subject of corporate sustainability, which is a management paradigm that has been accepted as a new approach against the growth and profit maximization approach that has been going on for years and has found a wide area of application in recent years, accepts that the issues of improvement, progress and profitability are indispensable, while defending the view that businesses, institutions, non-governmental organizations, etc. should also address sustainable development and environmental protection systems, justice and equality in social issues, economic progress and these issues should also be addressed from the perspective of stakeholders. The effect of organizational revenge intention on sustainability may result in negative results. Based on this assumption, the research will determine whether and in what direction the intention of revenge of employees towards their colleagues and managers in organizations affects the improvement, progress and profitability goals of the organizations.

The research problem is, does revenge intention have an effect on sustainability in organizations? If so, in what direction? The research universe is the employees working in civil aviation organizations operating in Istanbul province with an online survey method. The research universe is the group consisting of all people related to answering the determined problem (Lin, 1976: 146). However, the number of the universe makes the research impossible due to the limitations in time and financial resources. For this reason, a subset (sample) that will represent this group is selected from the entire group (universe) included in the research. Collecting information from a sample selected from the universe instead of the entire universe is a cheaper, faster and easier way (De Vasus, 1990: 60). Selecting a subset that represents the universe is called sampling and sample selection. Quota sample selection technique was used for the research. Quota sample selection technique starts with the description of the characteristics of the targeted universe. Certain quotas are created regarding the characteristics of the sample units and individuals are selected within the framework of these quotas. Quota sampling is a practical and economical technique. According to the criteria of the quota, the people interviewed will be more easily reached and those who are willing to participate in the research will be more represented in the sample (Sencer and Sencer, 1978: 482). In this research, data is collected between 01.10 – 01.12. 2024 for the sampling frame. The sample of the research is determined as 500 people.

A single province and a certain number of companies are used. Therefore, the quota sampling technique becomes practical and economical for the research. In this research, the dependent variable is organizational sustainability and the independent variable is organizational revenge intention.

Ethical approval for the study was obtained at the meeting of Istanbul Esenyurt University Ethics Committee dated 17 September 2024 and numbered 2024/07.

3.2. Measures

Data was collected in the study using the survey method. The first part of the survey includes a personal information form consisting of questions on gender, age, level of education, marital status, working with the current manager, and length of service in the organization. The second part includes the "Organizational Revenge Intention Scale", which consists of 5 items and was used with ethical permission from Yılmaz's (2019) master's thesis and measures organizational revenge intention. This scale is a 5-point Likert-type scale (1= Never, 2= Rarely, 3= Sometimes, 4= Frequently, 5= Always). Yılmaz (2019) calculated the reliability of the revenge intention scale as 0.81 in his master's thesis. The third part of the survey includes the "Organizational Sustainability Scale", which consists of 39 items and was used with ethical permission from Gültekin and Argon's (2020) article and measures organizational sustainability in terms of social, cultural, environmental, economic, and administrative aspects. This scale is a 5-point Likert-type scale (1=Strongly disagree, 2= Disagree, 3= Undecided, 4= Agree, 5= Strongly agree). In the article by Gültekin and Argon (2020), the Cronbach alpha coefficient of social sustainability, which are the sub-dimensions of the organizational sustainability scale, is 0.93, the Cronbach alpha coefficient of cultural sustainability is 0.89, the Cronbach alpha coefficient of environmental sustainability is 0.87, the Cronbach alpha coefficient of economic sustainability is 0.87, and the Cronbach alpha coefficient of administrative sustainability is 0.98. All these results show that the scale has high reliability. In this research study, 25 statements of organizational sustainability and the statements of environmental, economic and administrative sustainability from the sub-dimensions related to these statements are used.

3.3. Data analysis method

In order to determine the effect of organizational revenge intention on organizational sustainability, analyzes are made in SPSS statistical package program and SPSS AMOS graphic programs, statistics are calculated and modeling is done. The results obtained are interpreted in detail.

Frequency and percentage distributions and mean and standard deviation values are calculated to obtain descriptive and descriptive statistics for the analyses to be performed. Kurtosis and skewness values are used to determine the closeness to normal distribution. Confirmatory Factor Analysis from Structural Equation Modeling is used to verify the validity of the scales, and Structural Regression Analysis from Structural Equation Modeling is used to calculate the effect of the independent variable on the dependent variable.

4. Result and Analysis

4.1. Demographic characteristics

The frequency and percentage distributions of demographic questions such as gender, age, education level, marital status, working with the manager, and working time in the institution are shown in Table 1.

Table 1. Demographic Characteristics

Variable	Category	n	%
Gender	Male	224	44.8%
	Female	276	52.2%
Age	18-24 years	306	61.2%
	25-34 years	142	28.4%
	35-44 years	52	10.4%
Marital Status	Single	427	85.4%
	Married	73	14.6%
Education Level	High School	20	4.0%
	Associate Degree	70	14.0%
	Bachelor's Degree	410	82.0%
Working Time with Manager	Less than 2 years	365	73.0%
	2-5 years	86	17.2%
	6 years or more	49	9.8%
Working Time at Organization	Less than 1 year	283	56.6%
	1-5 years	146	29.2%
	6 years or more	71	14.2%
	Total	500	100%

The sample consists of 52.2% female (n=276) and 44.8% male (n=224) participants. A majority (61.2%, n=306) are between the ages of 18-24, while 28.4% (n=142) are aged 25-34, and 10.4% (n=52) are 35-44. Most employees are single (85.4%, n=427), and 82.0% (n=410) hold a bachelor's degree. Regarding tenure with their current manager, 73.0% (n=365) have been working with them for less than 2 years. In terms of organizational tenure, 56.6% (n=283) have been with their current organization for less than a year. Overall, the majority of employees have relatively short tenures both with their current manager and organization.

4.2. Descriptive Statistics

Descriptive statistics are statistics related to compiling, collecting, summarizing and analyzing numerical data. Mean and standard deviation values are used in descriptive statistics. Skewness and kurtosis are an indicator of how skewed or flat a distribution graph is compared to a normal distribution. If the kurtosis value is positive, the curve is steeper/sharper, and if it is negative, it is flatter. If the skewness coefficient is negative, it indicates a distribution skewed to the right, and if it is positive, it indicates a distribution skewed to the left. The kurtosis coefficient is 0 in a normal distribution. A positive kurtosis coefficient indicates a sharp distribution, and a negative kurtosis coefficient indicates a flat distribution. Table 2 shows the kurtosis and skewness values from descriptive statistics and normal distribution indicators. Table 2. Mean, Standard Deviation, Kurtosis and Skewness Statistics

Employees' perceptions of organizational revenge intention ($\bar{X}$= 3.457∓1.136), organizational sustainability ($\bar{X}$= 3.890 ∓ 0.597), administrative sustainability ($\bar{X}$= 4.211 ∓ 0.534), environmental sustainability ($\bar{X}$= 3.421 ∓ 0.936) and economic sustainability ($\bar{X}$= 3.457 ∓ 1.136) dimensions are high. The dimension with the highest perceptions is administrative sustainability. Since the kurtosis and skewness statistics in Table 2 are between ∓1.5, it can be stated that the variables are close to normal distribution.

Table 2. Mean Average, Standard Deviation, Kurtosis and **Skewness** Statistics

Variable	Mean	Std. Deviation	Kurtosis	Std. Error of Kurtosis	Skewness	Std. Error of Skewness
Organizational Revenge Intention (ORI)	3.457	1.136	-0.472	0.109	-0.533	0.218
Organizational Sustainability (OS)	3.890	0.597	-0.166	0.109	-0.850	0.218
Managerial Sustainability (MS)	4.211	0.534	-0.524	0.109	0.657	0.218
Environmental Sustainability (EvS)	3.421	0.936	-0.235	0.109	-0.763	0.218
Economic Sustainability (ES)	3.457	1.136	-0.472	0.109	-0.533	0.218

4.3. Reliability Analysis

The reliability of the factors is measured by the Cronbach alpha coefficient model called Reliability Analysis. The results of the reliability analysis are interpreted depending on the alpha coefficient (Kalaycı, 2008):

The reliability of the scales used in the study was assessed using Cronbach's alpha, with values for each scale ranging from 0.778 (for environmental sustainability) to 0.895 (for organizational revenge intention), all of which indicate a high level of internal consistency (Karasar, 1995).
According to Cronbach's alpha coefficient, organizational revenge intention, organizational sustainability, administrative and economic sustainability dimensions are at a high level of reliability, while the environmental sustainability dimension is at a very reliable level. These results show that the scales can be used for analysis.

Table 3. Cronbach Alpha Coefficients

Scale	Cronbach's Alpha Coefficient	n
Organizational Revenge Intention Scale (ORI)	0.895	4
Organizational Sustainability Scale (OS)	0.875	17
Managerial Sustainability Dimension (MS)	0.845	10
Environmental Sustainability Dimension (EvS)	0.778	5
Economic Sustainability Dimension (ES)	0.802	2

4.4. Confirmatory Factor Analysis

Confirmatory factor analysis is used with AMOS program to verify the validity of organizational revenge intention scales. Confirmatory factor analysis is one of the structural equation modeling. This analysis is used for scale development and validity analysis and aims to verify the previously determined structure. Confirmatory factor analysis tests or determines how the factor analytic structure of the data fits a hypothesized model. In confirmatory factor analysis, variables are accepted as functions of latent variables called factors. In confirmatory factor analysis, observed variables are associated only with previously determined latent variables. Correlation between some error terms is allowed. Some parameters are limited to certain values or are limited to have the same value as other parameters. In confirmatory factor analysis, first-order single-factor model, multi-factor model and second-order multi-factor model are derived (Bayram, 2013: 42). Figure 3 shows the confirmatory factor analysis model of organizational revenge intention.

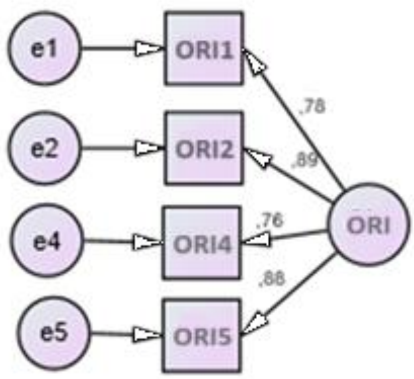

Figure 2. Organizational Revenge Intention Scale Single Factor Confirmatory Factor Analysis (CFA) Model

A single factor model consisting of a total of 4 observed variables was determined in the model that emerged as a result of the confirmatory factor analysis conducted on the organizational revenge intention (ORI) scale. According to the model fit indexes, the 3rd statement of the scale (3. I have a durable structure that can sustain my existence in line with my goals under all conditions) was removed from the model. After the analysis was repeated again, it was seen that the model fit indexes were between the required values. The fit results of the confirmatory factor model are shown in Table 3.

Table 3. Fit Indices: Second-Level Multi-Factor Model of Organizational Revenge Intention

CMIN	SD	CMIN/SD	RMR	RMSEA	GFI	CFI	IFI
3.712	2	7.424	0.026	0.074	0.993	0.996	0.996

∗ $p \leq 0,01$

The findings of the confirmatory factor analysis of the organizational revenge intention scale are 〖ΔX〗^2 =3.712, sd=2, 〖ΔX〗^2⁄sd= 7.424, RMR= 0.026, RMSEA=0.074, GFI=0.993, CFI=0.996 and IFI=0.996. Within the framework of this information, it is seen that the model shows acceptable fit according to the general model fit (≤4-5) result, the root mean square error of approximation, which is one of the comparative fit indices, RMSEA (0.06-008), shows acceptable fit and the residual-based fit index, RMR (≤0.05), shows good fit. According to the results of the goodness of fit index GFI (≥0.90), the incremental fit index IFI (≥0.95) and CFI (≥0.95), which are other absolute fit indexes, the model shows a good fit. The secondary level multi-factor model of the organizational sustainability scale is shown in Figure 4.

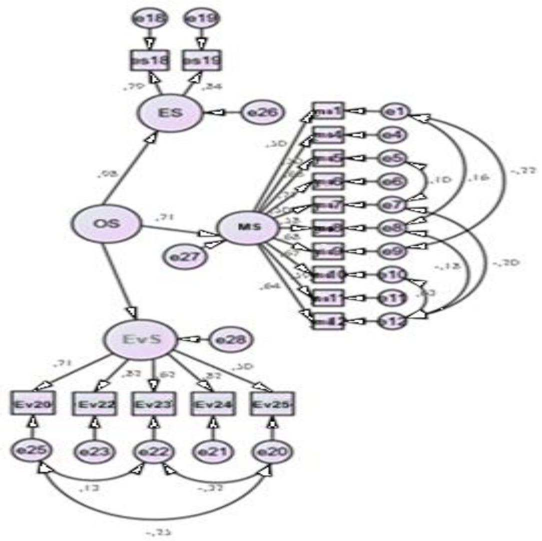

Figure 3. Secondary Level Multifactor Model of Organizational Sustainability Scale

The model obtained as a result of CFA regarding the organizational sustainability (OS) scale is seen to consist of a total of 17 observations and three factors. The statements of each factor are included in the model. A total of two statements of economic sustainability (ES) were included in the model and the other two statements (17. I implement effective savings programs (smart/photocell lamp, faucet, etc.) and 18. I try to create national awareness with actions such as encouraging people to buy local products) were removed from the model because their factor loadings were low and violated the determined compliance limits. While ten statements of managerial sustainability (MS) are included in the model, 5 statements (2. *''I benefit from my experiences to continue my existence in line with my goals''*, 3. I have a durable structure that can continue my existence in line with my goals under all conditions, 13. Our superiors in the institution are willing to help me shape the future, 14. Our superiors in the school have the experience to evaluate yesterday, today and tomorrow together, 15. Our superiors in the institution create a collaborative working environment) are not included in the model. Environmental sustainability (EvS) has a statement that is not included in the model because it has a low actor load and has a negative effect on the determined harmony (21. I use environmentally friendly products (ecological papers, natural cleaning materials, organic foods, etc.). Therefore, a total of 5 statements are included in the model. Table 4 shows the fit indices of the second-level multi-factor model of the organizational sustainability scale.

Table 4. Fit Indices: Second-Level Multi-Factor Model of Organizational Sustainability

CMIN	SD	CMIN/SD	RMR	RMSEA	GFI	CFI	IFI
2,772	86	238,403	0,049	0,060	0,949	0,961	0,961

* $p \leq 0,01$

The findings of confirmatory factor analysis of organizational sustainability scale are 〚ΔX〛^2 =2.772, sd=86, 〚ΔX〛^2⁄sd= 238.403, RMR= 0.049, RMSEA=0.060, GFI=0.949, CFI=0.961 and IFI=0.961. Within the framework of this information, it is seen that the model shows good fit according to the general model fit (≤3) result, the root mean square error of approximation, which is one of the comparative fit indexes, RMSEA (0.06-008), is acceptable fit and the residual-based fit index, RMR (≤0.05), also indicates good fit. According to the results of the goodness of fit index GFI (≥0.90), the incremental fit index IFI (≥0.95) and CFI (≥0.95), which are other absolute fit indexes, the model shows good fit.

4.5. Structural Regression Analysis ~~with SPSS AMOS~~

One of the SEM models that can be analyzed with AMOS is structural regression models. Structural regression models include confirmatory factor analysis models and path analysis at the same time. These models are models that can include observed and latent variables at the same time. Such models are used to discover the relationships of latent variables whose interactions are unknown (Meydan and Şeşen, 2011: 121). Figure 5 shows the path regression model of the effect of organizational revenge intention on organizational sustainability.

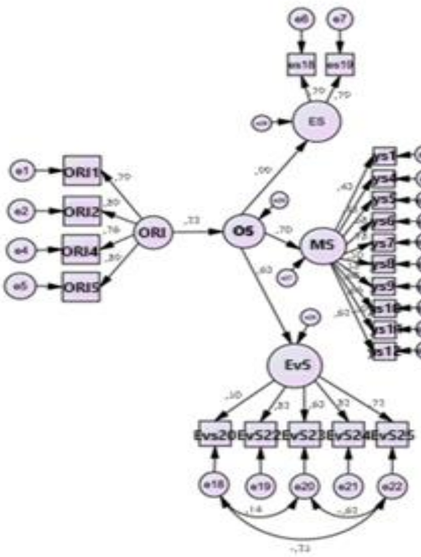

Figure 4. Structural Model: Organizational Revenge Intention and Sustainability

The organizational revenge intention scale is an independent variable consisting of 4 observed variables. The organizational sustainability scale is also included in the model as a dependent variable consisting of 17 observed variables. Table 5 shows the fit index results of the model regarding the effect of organizational revenge intention on organizational sustainability.

Table 5. Fit Indexes: Organizational Revenge Intention and Sustainability

CMIN	SD	CMIN/SD	RMR	RMSEA	GFI	CFI	IFI
2.772	148	369.302	0.068	0.055	0.938	0.958	0.959

* $p \leq 0,01$

The findings of the structural regression analysis regarding the effect of organizational revenge intention on organizational sustainability are 〚ΔX〛^2 =369.302, sd=148, 〚ΔX〛^2⁄sd= 2.772, RMR=0.068, RMSEA=0.055, GFI=0.938, CFI=0.958 and IFI=0.959. Within the framework of this information, according to the general model fit (≤3) result, the model shows a good fit, and according to the results of the root mean square error of approximation, RMSEA (0.06-0.008), which are comparative fit indexes, and RMR

(0.06-0.08), which is the residual-based fit index, the model indicates an acceptable fit. According to the results of the goodness of fit index GFI (≥0.90), the incremental fit index IFI (≥0.95) and CFI (≥0.95), which are other absolute fit indexes, the model shows a good fit. The regression weights of the model are shown in Table 6.

Table 6. Regression Results of the Model Regarding the Effect of Organizational Revenge Intention on Organizational Sustainability

B	Standard Error	p-value
0.230	0.040	0.000

Regression Results: Organizational Revenge Intention and Sustainability

In this study, the impact of organizational revenge intention on organizational sustainability has been assessed, with the results indicating that the model path is statistically significant, as shown by the p-value ($p \leq 0.01$). This finding suggests that perceived organizational support has a significant influence on employee performance. Specifically, the data reveals that employees' intention to engage in organizational revenge affects their organization's sustainability goals by 23%. To provide a more comprehensive analysis of this relationship, let us consider the various tables and statistical results presented.

Descriptive Statistics and Reliability Analysis: The descriptive statistics for the key constructs of organizational revenge intention (ORI), organizational sustainability (OS), managerial sustainability (MS), environmental sustainability (EVS), and economic sustainability (ES) show that all constructs have relatively high mean values, indicating that these factors are generally perceived positively by the respondents. The reliability of the scales used in the study was assessed using Cronbach's alpha, with values for each scale ranging from 0.778 (for environmental sustainability) to 0.895 (for organizational revenge intention), all of which indicate a high level of internal consistency. These findings suggest that the measurement tools used are reliable, contributing to the validity of the results.

Path Analysis Results: The results from the structural equation modeling (SEM) path analysis are crucial for understanding the relationships between the variables. The standardized path coefficient (β) between organizational revenge intention and organizational sustainability is 0.230, with a standard error of 0.040 and a p-value of 0.000. This suggests a strong, statistically significant positive relationship between organizational revenge intention and organizational sustainability. A β value of 0.230 means that a 1-unit increase in organizational revenge intention leads to a 0.23-unit increase in organizational sustainability, supporting the hypothesis that higher levels of revenge intention among employees are associated with lower sustainability outcomes for the organization.

Fit Indices and Model Evaluation: The fit indices for the structural model indicate good model fit: the CMIN/SD ratio is 7.424, the RMR is 0.026, and the RMSEA is 0.074, all of which are within acceptable ranges for confirming the model's fit to the data. Furthermore, the GFI (Goodness of Fit Index), CFI (Comparative Fit Index), and IFI (Incremental Fit Index) all show values close to 1, which further supports the robustness of the model.

Impact of Revenge Intention on Sustainability Goals: From a practical perspective, the results suggest that employees' intention to engage in organizational revenge has a notable negative effect on the achievement of sustainability goals, particularly affecting the organization's sustainability objectives by approximately 23%. This finding is significant because it highlights the potential organizational costs associated with unresolved interpersonal conflicts and negative emotions, such as revenge, among employees. Employees who harbor negative intentions, such as revenge, may undermine organizational efforts to achieve long-term sustainability goals, both from an environmental and economic perspective.

Implications for Organizational Sustainability: The study also offers valuable insights into the broader implications of organizational behavior on sustainability. The significant relationship between revenge intention and sustainability suggests that fostering a positive organizational climate is critical for maintaining progress toward sustainability goals. Organizations need to address underlying issues, such as conflict resolution, perceived organizational support, and employee engagement, in order to reduce the potential for harmful behaviors like revenge, which can undermine sustainability efforts.

5. Discussion and Conclusion

In this study, findings were obtained examining the effect of employees' organizational revenge intention on organizational sustainability. As a result of the analyzes, it was determined that organizational revenge intention has a 23% effect on organizational sustainability. This result shows that employees' acting with organizational revenge motivation can have a significant negative impact on the long-term success and sustainability goals of companies. In this section, the findings will be compared with other similar studies in the literature and suggestions for future research will be presented. The findings of this study reveal that employees' revenge motives can negatively affect not only their individual work efficiency but also the organization's overall sustainability goals. The damage to employees' sense of justice can negatively affect their commitment and motivation to the organization. The effect of organizational revenge motivation indicates that employees may tend to intentionally sabotage their work, exhibit destructive behaviors, and damage organizational culture. This situation can pose a serious threat to the sustainability of companies.

Considering that organizational sustainability includes not only economic but also social and environmental factors, such negative behaviors of employees can harm the overall strategic goals of the organization. This finding reveals that organizations should focus more on improving employees' perception of justice and combating favoritism when creating sustainability strategies.

Recommendations

Fair Human Resources Management: One of the main factors that feed employees' revenge instinct is injustice and favoritism in the workplace. For this reason, companies need to develop fair, transparent and inclusive practices in human resources management. Objective criteria should be determined in the recruitment, promotion and reward processes, and discrimination should not be allowed among employees. Eliminating such injustices can strengthen employees' ties to the organization and reduce the revenge instinct.

Education and Awareness Programs: Education and awareness programs should be organized to develop employees' understanding of organizational justice and sustainability. These trainings can create awareness about both sustainability principles and employee rights. Trainings can provide information about how employees contribute to the company's strategic goals and how individual interests overlap with organizational goals.

Employee Participation and Feedback Mechanisms: Ensuring employees' participation in management processes in the workplace can motivate them more and reduce feelings of injustice in the workplace. Feelings of organizational revenge can be prevented by establishing feedback mechanisms where employees can directly interact with management. Regular surveys and feedback sessions can provide employees with a voice.

Reviewing Corporate Sustainability Strategies: Companies should consider not only environmental and economic factors but also social factors when developing their sustainability strategies. Factors such as employee satisfaction, workplace fairness, and workforce diversity should be made core elements of sustainability strategies. Social sustainability is a critical component for the long-term success of organizations.

Proactive Management in Crisis Situations: Especially during times of crisis, employees’ trust in the workplace can be quickly damaged. Therefore, a transparent and fair communication strategy that provides support to employees should be followed during crisis management processes. In addition, policies that consider employees’ psychological and work-related well-being should be developed during post-crisis recovery processes.

Limitations of the Study: There are some limitations to this study. First, the sample group is limited to employees in the aviation sector only, so it can be said that the findings are specific to this sector. The validity of the same results for employees in other sectors is questionable. The study is survey research conducted specifically focusing on a specific geographical region, which may lead to ignoring differences in different cultural, economic and social contexts. In addition, the cross-sectional nature of the data makes it difficult to clearly reveal causal relationships. Long-term studies may provide an opportunity to examine the relationship between employees' revenge motivations and organizational sustainability in more depth.

Another limitation is the analyses conducted with data based on participants' self-reports. Such data carry the risk of the responses being based on social acceptability and personal perceptions. In addition, the concept of organizational sustainability is a multidimensional and comprehensive term, and only a part of it has been addressed in this study. The study did not comprehensively address the environmental and social dimensions of sustainability.

Contribution to the Literature: This study makes a significant contribution to the existing literature by investigating the effects of organizational revenge intentions on organizational sustainability. The study particularly emphasizes the motivational consequences of negative work environments such as favoritism and injustice on employees and how these interact with organizational sustainability goals. While the existing literature mostly addresses the negative emotional reactions of employees and their consequences at the individual level, this study offers a broader perspective by directly connecting with the concept of organizational sustainability. In addition, this research provides sector-specific contributions by addressing the relationship between perception of justice and organizational revenge, especially in the context of the aviation sector.

The study suggests a more holistic approach by relating the concept of organizational sustainability not only to economic factors but also to social and environmental factors . This is an important finding that shows that social factors such as employee satisfaction and workforce motivation should also be included in sustainability research.

Future Study Recommendations: Although this study examined the impact of organizational revenge intentions on organizational sustainability, future studies can address the issue more deeply and from different perspectives. First, conducting long-term studies can reveal how revenge intentions affect organizational sustainability over time. In addition, comparative studies conducted on organizations in different sectors can increase the generalizability of the findings and reveal the impact of sector-specific factors more clearly.

Another recommendation is to increase research on how the perception of organizational justice can be associated with leadership styles and management strategies in particular. Future studies can examine the effects of leadership and organizational structures on revenge motivations, emphasizing that justice should be managed not only as a perception but also as a strategy.

In addition, conducting such studies in various cultural contexts can help us understand the impact of cultural differences on revenge intentions and sustainability. Comparative studies conducted in different countries and with different organizational structures will better reflect the diversity of sustainability strategies in the global business world.

Finally, the concept of organizational sustainability should be considered more broadly, taking into account not only employee satisfaction and revenge intentions but also other sustainability dimensions such as environmental and social responsibility. Such multidimensional studies will allow organizations to embark on a more balanced and sustainable development path.

Ethical approval

The ethical approval for this research was granted by the Istanbul Esenyurt University Scientific Research and Publication Ethics Committee with the decision number 2024/07, dated 17.09.2024. The committee confirmed that the research was deemed ethically appropriate.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Evaluating Non-Technical Skills of Airline Pilot Candidates Using an Analytic Hierarchy Process (AHP) Approach

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Abstract

This study evaluates the non-technical skills (NOTECHS) of airline pilot candidates using the Analytical Hierarchy Process (AHP) approach. It aims to determine the importance and weighting of these skills in pilot selection processes. Nine non-technical competencies used in pilot selection within a Turkish aviation company were identified and weighted based on their importance across various flight stages (preflight, take-off, cruise, approach/landing, taxi) using the AHP technique. Scenarios based on real flight operations were evaluated by experienced flight examiners. The analysis revealed that situation awareness, problem-solving, and decision-making were the most critical non-technical skills across all phases of flight. Leadership and communication also played significant roles, while planning and professional development were less critical. As a result of the analysis, theoretical and practical suggestions in the field of aviation were presented.

1. Introduction

Commercial aviation is one of the world's largest industries, and ensuring safe operations requires professionalism and coordination among a wide range of professionals, including pilots, who are a critical human factor. Research shows that pilot error accounts for a significant portion of these accidents (IATA, 2021; Kaya & Ates, 2023; Lenné et al., 2008; Li et al., 2001; Oster et al., 2010; Wiegmann et al., 2005). Over the last 100 years, numerous studies have been conducted on pilot selection. With a growing need for pilots (Airbus, 2023; Boeing, 2023; CAE, 2023), the emphasis on selecting pilots with both technical and non-technical skills (NOTECHS) has increased. Aviation regulators, responsible for safety oversight worldwide, now require airlines to focus on selecting pilots who are a good 'fit' for the airline (Bor et al., 2020) and emphasize the importance of competencies for aviation professionals (Tuncal & Çınar, 2024). Pilots are chosen not only for technical flight skills but also for non-technical skills (NOTECHS), such as situational awareness, decision-making, leadership, teamwork, and stress management. Recent studies examining the relationship between pilot selection and non-technical competencies (Goeters et al., 2004; Hedge et al., 2000; Hörmann et al., 2022; Ruff-Stahl et al., 2016) highlight the importance of these skills. The European Association of Aviation Psychology (EAAP) stated in its 2022 "*Selection in Aviation*" report that, while pilot selection criteria align with IATA's qualifications, the measurement and weighting of these competencies vary. Institutions should clarify how they weigh these measures in selection tools (Eaglestone et al., 2022). This proposition is in line with the requirement that each qualification criterion, from the beginner pilot to the licensed pilot, be weighted, as stated in the "*Pilot Aptitude Testing Guidance Material and Best Practices*" report published by IATA in 2019 (International Air Transport Association, 2019). However, IATA does not provide information regarding these measurement and weighting details. A review of the literature reveals that no study has been found to determine the weighting and importance level based on non-technical skills (NOTECHS) in the direct pilot selection process. The present study aims to determine the importance of non-technical skills that affect the human factor in pilot selection processes and how these skills should be weighted. Therefore, the competency dimensions actively used in pilot selection processes in an aviation company and included in the scope of the research were weighted with the Analytical Hierarchy Process (AHP).

2. Literature Review

Pilot selection has its roots in early 20th-century military aviation, shaped by the need for skilled pilots in warfare. Modern civil aviation selection processes begin with training and licensing, followed by tests in knowledge, psychomotor skills, group evaluations, simulator qualifications, and interviews (Zinn et al., 2019). Crew Resource Management (CRM) supports safe behaviors and now covers non-technical skills like situational awareness, decision-making, and fatigue management (IATA, 2023). CRM training expanded from its original scope to include broader human factors (Civil Aviation Authority, 2016).

Non-technical skills (NOTECHs), vital for professions requiring technical expertise, refer to cognitive and social abilities unrelated to aircraft control. Introduced by the European Joint Aviation Association (JAA), NOTECHs focus on areas like cooperation, leadership, and decision-making (Flin et al., 2008). These competencies, evaluated through the Advanced Qualifications Program (AQP) by the Federal Aviation Administration (FAA), are mandatory in the UK (Flin, 2010). ICAO defines eight core competencies, including communication, problem-solving, leadership, and workload management (Mansikka et al., 2017).

Studies conducted by Yazgan and Ustun (2011) and Yazgan and Erol (2016) classified pilot selection criteria into three main groups: technical, non-technical, and work-oriented. These studies determined that the most important criteria were intelligence, decision-making and problem-solving ability, and psychomotor skills, using the Analytical Hierarchy Process (AHP) technique. In addition, Oktal and Onrat (2020) and Mızrak (2023) identified flight skills, personality traits, and English language proficiency as the most critical criteria by weighting the pilot competencies defined by IATA and the evaluation criteria in the recruitment processes of civil aviation pilots. Similarly, Şimşek et al. (2022) emphasized that safe flight operations in the aviation sector, characterized by strict regulations and intense competition, depend on employing qualified human resources who can adapt to technology. Their research, which utilized the AHP method, focused on identifying the most suitable candidates in pilot recruitment processes by consulting senior pilots from the world's top 10 airlines. Based on the recommendations of experienced captains with managerial roles, 17 criteria (3 upper and 14 sub-criteria) actively used in the sector were weighted. As a result of their analysis, "technical," "non-technical," and "occupational criteria" were ranked as the upper criteria according to their importance based on local weights. In the context of the relevant literature, the following methodological paths were designed in this research.

3. Materials and Methods

The research aims to answer the following questions:

RQ1: What are the non-technical skills used in pilot selection processes, and how are these skills weighted according to flight phases?

RQ2: How do the weights of non-technical skills used in pilot selection processes change during flight phases such as pre-flight, take-off, cruise, approach and landing, and taxi?

RQ3: What non-technical competencies are considered most important in pilot selection processes?

There are two studies in the research. In the first study, nine non-technical competencies (*situation awareness, problem solving and decision making, teamwork, leadership, communication, controlling and managing emotions, planning, sense of duty, professional development*) used in pilot selection processes were identified and defined (Table 1). Competency dimensions utilized in this study were derived from the competency framework outlined in the International Air Transport Association's (IATA) (2019) document, *Competency Assessment and Evaluation for Pilots, Instructors, and Evaluators*. These competencies have been adapted and structured into a set comprising nine dimensions by a collaborative team of examiner pilots and academics currently working at an aviation company operating in Türkiye. This competency set is actively employed during the selection processes for first officer candidates within the company's assessment center framework.

Table 1. Non-technical Criterias and Explanations

Non-technical Criteria	Description
Situation Awareness	The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and a projection of their status in the near future (Endsley, 1988).
Problem Solving and Decision Making	The personnel working in high-risk sectors, under high-stress conditions and pressures originating from the need to make quick decisions in a very short time (Ceschi et al., 2019).
Teamwork	A dynamic process involving two or more professionals with complementary background and skills contributing in the most effective way to the overall tasks and goals of the team (Civil Aviation Safety Authority, 2019).
Leadership	In the context of influence, and explains how the leader should recognise the desires of the crew, set an example and use persuasion to create an understanding of goals that need to be met (ICAO, 2013)
Communication	The exchange of information, feedback or response, ideas and feelings (Flin et al., 2008).
Controlling and Managing Emotions	Provide a framework for both individual and organisational involvement in minimising stressful events and reactions (Flin et al., 2008).
Planning	Includes the processes of prioritization, resource management, alternative creation, time management, and plan control (Gontar & Hoermann, 2016).
Sense of Duty	It is the responsibility to perform one's duties effectively and ethically, which includes competencies such as business mastery, representativeness, self-discipline, compliance with rules and procedures, error awareness, and honesty (ICAO, 2010).
Professional Development	The process of continuously improving one's knowledge and skills through competencies such as resolving deficiencies/acquiring knowledge, motivation to learn, keeping one's knowledge up to date, being open to feedback, and learning from experiences.

To determine the weight of these competencies, the flight operation was divided into five basic flight phases. Scenarios were created for each flight phase based on real flight operations together with 5 Instructor Pilots. The criteria for selecting pilots during the scenario phase included having more than 10,000 hours of flight experience, being an Instructor, and having served in the assessment center of the relevant aviation company. These pilots did not participate in the weighting process. In the Evidence-Based Training document published by the International Civil Aviation Organization (ICAO) in 2013, it is stated that developing, training, and evaluating competencies using operational scenarios (ICAO, 2013). Additionally, Helmreich et al. (1999) suggested that rating flight crew behavior by flight phase. Table 2 lists the flight phases assigned for this research and the scenarios specific to each flight phase. Three sample scenarios are provided for each flight phase in the survey.

Table 2. Non-technical Criterias and Explanations

Phases	Sample Scenarios
Pre-flight	The pressurization system, which should have remained in automatic mode, was left in manual mode due to an item that was missed in the checklist during ground operation checks. Shortly after takeoff, everyone on board fainted.
Takeoff & Climb	The landing gear was forgotten to be retracted after takeoff. (*There is no after-take-off checklist in Airbus procedures.*)
Cruise	Suddenly, while flying over the ocean during a night flight, the fire alarms went off, and the flight crew could not identify the source of this warning for a while.
Approach and Landing	During a training flight, a first officer candidate, panicking and saying 'I can't land', let go of the controls. The captain pilot then safely landed the aircraft at the last moment.
Taxi-in	By following ATC (air traffic control) instructions to enter a taxiway not suitable for the wingspan, the aircraft veered off the taxiway and struck a tower in the grass area, resulting in a broken wing.

In the second study, sample scenarios were presented to 10 Examiner Pilots employed in the relevant aviation company via an online questionnaire and face-to-face interviews, and nine non-technical competencies for each flight phase were weighted using the Analytical Hierarchy Process technique.

The research model created is shown in the figure below (Figure 1):

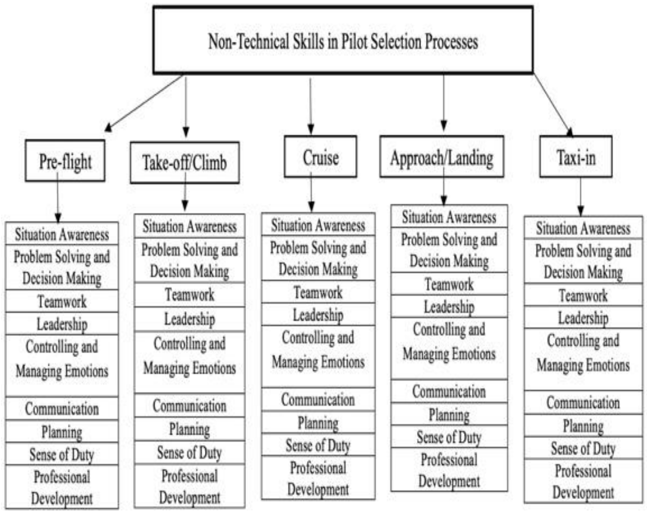

Figure 1. Research Model

Flight Examiners, as defined by the General Directorate of Civil Aviation (2024), are pilots authorized to carry out the tests and checks required for the issuance, revalidation, or renewal of any pilot license or rating. In addition to their administrative and technical duties, these experts, all of whom are instructor pilots, are evaluated to have a high level of competency in terms of pilot employment. Therefore, the sample group for this study consisted of Examiner Pilots. The data obtained was analyzed using the Analytical Hierarchy Process (AHP) analysis technique using Microsoft Excel 2016. During the analyses, we collaborated with a faculty member from the Numerical Methods Department, whose area of expertise is Multiple Decision Making Methods. During the consistency analysis, a participant who could not obtain evaluation findings in line with the consistency rate was removed from the sample group based on expert opinion.

4. Results

The demographic characteristics of the participants are presented in the Table 3. According to the demographic information in the table, all participants are male with an average age of 49.3. The participants' average flight hours were found to be 13200 hours, and their average flight seniority as examiner pilots was found to be 7 years.

Table 3. Demographic Characteristics

P	Gender	Education	Age	Status	TFH	TFY	YSEP
P1	Male	Air Force Academy	52	Examiner Pilot	13000	20+	7
P2	Male	Masters Degree	56	Examiner Pilot	18000	20+	15+
P3	Male	Bachelor's Degree	42	Examiner Pilot	10000	11-15	2
P4	Male	Air Force Academy	50	Examiner Pilot	15000	20+	8
P5	Male	Masters Degree	50	Examiner Pilot	15800	20+	4
P6	Male	Bachelor's Degree	55	Examiner Pilot	13000	20+	8
P7	Male	Air Force Academy	51	Examiner Pilot	9600	20+	4
P8	Male	Masters Degree	45	Examiner Pilot	13000	16-20	6
P9	Male	PhD	43	Examiner Pilot	12000	20+	10

P = Participants; **TFH** = Total Flight Hours; **TFY** = Total Flight Years; **YSEP** = Years of Seniority as Examiner Pilot

Weighting operations using the Analytic Hierarchy Process (AHP) according to upper and lower criteria were conducted through the following steps. To determine the local and global weights of each sub-criterion, (1) pair-wise comparison matrices were created, and (2) comparison matrices were normalized. Following these procedures, the priority vectors of the criteria in the hierarchical structure were determined, and their consistency was checked. This process was repeated for each flight phase.

4.1. Pre-flight Phase

The normalization process for the pre-flight phase criteria is shown in the table. Normalization was performed by dividing each element of the pair-wise comparison matrix by the total value of the column. The priority vector of each criterion was calculated by taking the average of the elements in each row of the normalized matrix (Table 4).

Table 4. Normalized Matrix and Priority Vector Values for the Pre-flight Phase

	C1	C2	C3	C4	C5	C6	C7	C8	C9	PV
C1	0.056	0.076	0.055	0.055	0.089	0.06	0.053	0.025	0.057	**0.058458**
C2	0.104	0.142	0.191	0.158	0.158	0.159	0.172	0.173	0.182	**0.160036**
C3	0.154	0.112	0.151	0.217	0.184	0.115	0.139	0.123	0.143	**0.148589**
C4	0.164	0.143	0.111	0.159	0.158	0.215	0.168	0.185	0.173	**0.164054**
C5	0.041	0.059	0.054	0.066	0.065	0.077	0.083	0.088	0.052	**0.064948**
C6	0.053	0.05	0.075	0.042	0.048	0.057	0.06	0.079	0.047	**0.056821**
C7	0.179	0.139	0.184	0.161	0.134	0.159	0.169	0.189	0.162	**0.163903**
C8	0.161	0.059	0.088	0.062	0.053	0.051	0.064	0.072	0.096	**0.078398**
C9	0.087	0.221	0.092	0.081	0.11	0.106	0.092	0.066	0.088	**0.104792**

Criteria: C1: Sense of Duty, **C2:** Situation Awareness, **C3:** Problem Solving and Decision Making, **C4:** Teamwork, **C5:** Leadership, **C6:** Professional Development, **C7:** Communication, **C8:** Controlling and Managing Emotions, **C9:** Planning; **PV:** Priority Vector

In the table below, the pre-flight phase criteria are shown along with the calculated consistency index (Table 5). To ensure an acceptable consistency ratio (CR), the CR value must be 0.1 or less than 0.1.

Table 5. Consistency Ratio for Pre-flight Phase

Landa Max	Consistency Index (CI)	Random Index (RI)	Consistency Ratio (CR)
9.43295	0.054118614	1.45	**0.037323182** < 0.10

While calculating the overall weight, the priority vector of the main criterion to which the sub-criterion belongs is multiplied by the sub-criterion's own (local) priority vector. The table below lists the general weights and order of importance for the pre-flight phase (Table 6).

As a result of the calculations, the most important criteria in the pre-flight phase are leadership (0.03281), sense of duty (0.03278), problem solving and decision making (0.03200), respectively. Communication has the least importance at this stage with 0.01136.

Table 6. The Order of Importance of the Pre-flight Phase Factors

Pre-flight Phase	Leadership	**0.03281**
	Sense of Duty	**0.03278**
	Problem Solving and Decision Making	**0.03200**
	Teamwork	**0.02971**
	Planning	**0.02095**
	Controlling and Managing Emotions	**0.01567**
	Professional Development	**0.01298**
	Situation Awareness	**0.01169**
	Communication	**0.01136**

4.2. Take-off/Climb Phase

The priority vector of each criterion was calculated by taking the average of the elements in each row of the normalized matrix (Table 7).

Table 7. Normalized Matrix and Priority Vector Values for the Takeoff/Climb Phase

	C1	C2	C3	C4	C5	C6	C7	C8	C9	PV
C1	0.054	0.054	0.033	0.033	0.051	0.04	0.08	0.083	0.105	**0.059143**
C2	0.201	0.201	0.328	0.228	0.225	0.134	0.199	0.197	0.189	**0.211268**
C3	0.182	0.069	0.112	0.092	0.198	0.17	0.122	0.099	0.16	**0.133746**
C4	0.181	0.096	0.133	0.109	0.068	0.115	0.098	0.128	0.105	**0.11466**
C5	0.096	0.08	0.051	0.144	0.089	0.062	0.105	0.11	0.093	**0.092126**
C6	0.076	0.083	0.036	0.053	0.079	0.055	0.061	0.035	0.035	**0.057076**
C7	0.103	0.153	0.139	0.168	0.129	0.137	0.151	0.15	0.148	**0.141991**
C8	0.061	0.095	0.105	0.079	0.075	0.149	0.094	0.093	0.077	**0.091882**
C9	0.046	0.17	0.062	0.093	0.086	0.139	0.091	0.107	0.089	**0.098108**

Criteria: C1: Sense of Duty, **C2:** Situation Awareness, **C3:** Problem Solving and Decision Making, **C4:** Teamwork, **C5:** Leadership, **C6:** Professional Development, **C7:** Communication, **C8:** Controlling and Managing Emotions, **C9:** Planning; **PV:** Priority Vector

In the table below, the take-off/climb phase criteria are shown along with the calculated consistency index (Table 8).

Table 8. Consistency Ratio for Takeoff/Climb Phase

Landa Max	Consistency Index (CI)	Random Index (RI)	Consistency Ratio (CR)
9.46203	0.057754588	1.45	**0.039831** < 0.10

The table below lists the general weights and order of importance for the take-off/climb phase (Table 9).

In the calculations made in the take-off/climb phase, problem solving and decision making (0.04225) and sense of duty (0.02839) are the most important criteria. Situation awareness 0.01182 and communication 0.01141 have the least importance at this stage.

Table 9. The Order of Importance of the Take-off/Climb Phase Factors

Take-off/Climb Phase	Problem Solving and Decision Making	**0.04225**
	Sense of Duty	**0.02839**
	Teamwork	**0.02674**
	Leadership	**0.02293**
	Planning	**0.01962**
	Professional Development	**0.01842**
	Controlling and Managing Emotions	**0.01837**
	Situation Awareness	**0.01182**
	Communication	**0.01141**

4.3. Cruise Phase

The priority vector of each criterion was calculated by taking the average of the elements in each row of the normalized matrix (Table 10).

Table 10. Normalized Matrix and Priority Vector Values for the Cruise Phase

	C1	C2	C3	C4	C5	C6	C7	C8	C9	PV
C1	0.064	0.068	0.033	0.069	0.072	0.049	0.068	0.094	0.072	**0.065467**
C2	0.217	0.227	0.45	0.363	0.218	0.21	0.217	0.236	0.195	**0.259303**
C3	0.245	0.064	0.126	0.162	0.222	0.153	0.165	0.165	0.14	**0.160237**
C4	0.08	0.053	0.067	0.085	0.104	0.138	0.102	0.127	0.124	**0.097811**
C5	0.06	0.07	0.038	0.055	0.067	0.092	0.071	0.072	0.086	**0.067989**
C6	0.064	0.053	0.041	0.03	0.036	0.049	0.047	0.051	0.05	**0.046915**
C7	0.157	0.175	0.128	0.139	0.158	0.173	0.167	0.137	0.154	**0.154147**
C8	0.049	0.069	0.055	0.048	0.067	0.068	0.087	0.072	0.11	**0.069415**
C9	0.063	0.221	0.063	0.048	0.055	0.068	0.076	0.046	0.07	**0.078716**

Criteria: C1: Sense of Duty, **C2:** Situation Awareness, **C3:** Problem Solving and Decision Making, **C4:** Teamwork, **C5:** Leadership, **C6:** Professional Development, **C7:** Communication, **C8:** Controlling and Managing Emotions, **C9:** Planning; **PV:** Priority Vector

In the Table 11, cruise phase criteria are shown along with the calculated consistency index.

Table 11. Consistency Ratio for Cruise Phase

Landa Max	Consistency Index (CI)	Random Index (RI)	Consistency Ratio (CR)
9.52060	0.065075962	1.45	**0.044879974** < 0.10

The table below lists the general weights and order of importance for the cruise phase (Table 12).

In the calculations made for the cruise phase, situation awareness 0.05186 is identified as the most important criterion. Professional Development has the least importance rating at this stage, with a value of 0.00938.

Table 12. The Order of Importance of the Cruise Phase Factors

Cruise Phase	Situation Awareness	**0.05186**
	Problem Solving and Decision Making	**0.03204**
	Communication	**0.03082**
	Teamwork	**0.01956**
	Planning	**0.01574**
	Controlling and Managing Emotions	**0.01388**
	Leadership	**0.01359**
	Sense of Duty	**0.01309**
	Professional Development	**0.05186**

4.4. Approach/Landing Phase

The priority vector of each criterion was calculated by taking the average of the elements in each row of the normalized matrix (Table 13).

Table 13. Normalized Matrix and Priority Vector Values for the Approach/Landing Phase

	C1	C2	C3	C4	C5	C6	C7	C8	C9	PV
C1	0.052	0.049	0.031	0.038	0.047	0.101	0.065	0.072	0.058	**0.056874**
C2	0.262	0.248	0.384	0.337	0.309	0.214	0.348	0.239	0.253	**0.288149**
C3	0.253	0.096	0.149	0.159	0.212	0.102	0.165	0.127	0.215	**0.164237**
C4	0.131	0.07	0.089	0.095	0.112	0.131	0.068	0.137	0.101	**0.103672**
C5	0.07	0.051	0.044	0.053	0.063	0.071	0.068	0.086	0.084	**0.065747**
C6	0.026	0.059	0.075	0.037	0.045	0.051	0.052	0.027	0.036	**0.045528**
C7	0.105	0.093	0.117	0.181	0.121	0.129	0.131	0.182	0.137	**0.132924**
C8	0.042	0.061	0.068	0.04	0.043	0.11	0.042	0.058	0.052	**0.057268**
C9	0.057	0.273	0.044	0.06	0.048	0.091	0.061	0.072	0.064	**0.085602**

Criteria: C1: Sense of Duty, **C2:** Situation Awareness, **C3:** Problem Solving and Decision Making, **C4:** Teamwork, **C5:** Leadership, **C6:** Professional Development, **C7:** Communication, **C8:** Controlling and Managing Emotions, **C9:** Planning; **PV:** Priority Vector

In the table below, approach/landing phase criteria are shown along with the calculated consistency index (Table 14).

Table 14. Consistency Ratio for Approach/Landing Phase

Landa Max	Consistency Index (CI)	Random Index (RI)	Consistency Ratio (CR)
9.69169	0.086461943	1.45	**0.059628926** < 0.10

The table below lists the general weights and order of importance for the approach/landing phase (Table 15).

In the weighting calculations for the approach/landing phase, situation awareness (0.06228) is the most important criterion. This importance is followed by problem solving and decision making (0.02896) and teamwork (0.01993). Professional Development has the least importance rating at this stage, with a value of 0.00899

Table 15. The Order of Importance of the Approach/Landing Phase Factors

Approach/Landing Phase	Situation Awareness	**0.06228**
	Communication	**0.02966**
	Problem Solving and Decision Making	**0.02896**
	Teamwork	**0.01993**
	Planning	**0.01594**
	Leadership	**0.01322**
	Sense of Duty	**0.01069**
	Controlling and Managing Emotions	**0.01029**
	Communication	**0.01141**

4.5. Taxi-in Phase

The priority vector of each criterion was calculated by taking the average of the elements in each row of the normalized matrix (Table 16).

Table 16. Normalized Matrix and Priority Vector Values for the Taxi-in Phase

	C1	C2	C3	C4	C5	C6	C7	C8	C9	PV
C1	0.054	0.054	0.033	0.033	0.051	0.04	0.08	0.083	0.105	**0.059143**
C2	0.201	0.201	0.328	0.228	0.225	0.134	0.199	0.197	0.189	**0.211268**
C3	0.182	0.069	0.112	0.092	0.198	0.17	0.122	0.099	0.16	**0.133746**
C4	0.181	0.096	0.133	0.109	0.068	0.115	0.098	0.128	0.105	**0.11466**
C5	0.096	0.08	0.051	0.144	0.089	0.062	0.105	0.11	0.093	**0.092126**
C6	0.076	0.083	0.036	0.053	0.079	0.055	0.061	0.035	0.035	**0.057076**
C7	0.103	0.153	0.139	0.168	0.129	0.137	0.151	0.15	0.148	**0.141991**
C8	0.061	0.095	0.105	0.079	0.075	0.149	0.094	0.093	0.077	**0.091882**
C9	0.046	0.17	0.062	0.093	0.086	0.139	0.091	0.107	0.089	**0.098108**

Criteria: C1: Sense of Duty, **C2:** Situation Awareness, **C3:** Problem Solving and Decision Making, **C4:** Teamwork, **C5:** Leadership, **C6:** Professional Development, **C7:** Communication, **C8:** Controlling and Managing Emotions, **C9:** Planning; **PV:** Priority Vector

In the table below, taxi-in phase criteria are shown along with the calculated consistency index (Table 17).

Table 17. Consistency Ratio for Taxi-in Phase

Landa Max	Consistency Index (CI)	Random Index (RI)	Consistency Ratio (CR)
9.46203	0.057754588	1.45	**0.039831** < 0.10

The table below lists the general weights and order of importance for the approach/landing phase (Table 18).

Table 18. The Order of Importance of the Taxi-in Phase Factors

Taxi-in Phase	Situation Awareness	**0.05763**
	Problem Solving and Decision Making	**0.03284**
	Communication	**0.02658**
	Teamwork	**0.02073**
	Planning	**0.01712**
	Leadership	**0.01314**
	Controlling and Managing Emotions	**0.01145**
	Sense of Duty	**0.01137**
	Professional Development	**0.00910**

In the weighting calculations for taxi-in phase, situation awareness (0.05763) is identified as the most important criterion. This is followed by problem solving and decision making 0.03284. Professional Development (0.00899) and sense of duty (0.01137) have the least importance at this stage.

Finally, within the scope of the third research question, examiners scored non-technical skills with the AHP technique according to their importance in the pilot selection process, regardless of the flight phases. The global weights of the data were calculated, and the importance levels are listed below (Table 19). In the weighting calculations, situation awareness 0.13365 is identified as the most important criterion among all criteria, including non-technical skills. Planning has the least important level, with an overall severity level of 0.10206.

Table 19. The Order of Importance of the Non-technical Criteria for Pilot Selection Process

Criteria	Situation Awareness	**0.13365**
	Problem Solving and Decision Making	**0.11497**
	Sense of Duty	**0.11240**
	Communication	**0.11223**
	Professional Development	**0.11095**
	Controlling and Managing Emotions	**0.10907**
	Leadership	**0.10233**
	Teamwork	**0.10231**
	Planning	**0.10206**

5. Discussion

Weightings were determined using the Analytical Hierarchy Method (AHP) within the context of sample scenarios presented to 10 Examiner Pilots working in human resources, personnel selection, and pilot licensing duties in an aviation company. As a result of consistency ratio calculations, the importance levels of non-technical criteria for each flight phase were determined based on the general and local weights obtained by considering the scoring scores of nine participants. Situation awareness competency, which is predominant in three of the evaluated phases and in the overall weighting, is recognized as one of the most critical and essential skills for flight missions and flight crews. This finding aligns with the finding that situation awareness is the most critical skill during the approach, landing, and taxi phases (Shook et al., 2000). When examining general aviation accidents, the primary causes are largely attributed to the loss of situation awareness (Hunter, 1995; National Transportation Safety Board, 1989). This is particularly evident in the pre-flight phase, where gathering information and planning related to the flight it conditions (such as weather, air traffic control, airport location) are crucial. It is assumed that improving these evaluation behaviors (Prince and Salas, 1993) will enhance overall safety. Situation awareness, recognized as a critical competency in pilot selection processes (Helmreich and Foushee, 2019; Goeters et al., 2004; Gontar and Hoermann, 2014; Ruff-Stahl et al., 2016), directly impacts flight operation efficiency and performance today. Problem-solving and decision-making skill, which rank as the second most important in the weightings, represent a systematic approach to the cognitive process by which pilots select the best course of action in response to a given set of situations. In-flight decision-making was a contributing factor in 10% of all accidents (62) between 2012 and 2021 (International Air Transport Association, 2020). In addition to these two competencies, communication skills, which are highly ranked and considered fundamental for pilots by authorities, can also lead to a loss of situational awareness among team members and harm teamwork, as 60-70% of aviation accidents are attributed to communication failures (Federal Aviation Administration, 2004; International Air Transport Association, 2020). The Sully Accident, which is prominently discussed in the literature and based on decision-making skills and communication skills, serves as a prime example of this. In this incident, the pilots had to make a forced landing in the Hudson River after both engines failed. The effective application of CRM and efficient communication between cockpit-cockpit and cockpit-air traffic control (ATC) resulted in a safe landing with no fatalities (National Transportation Safety Board, 2010). Research findings (Salas et al., 2008; Sexton et al., 2000) in the literature indicate that teamwork and collaboration, which are other prominent competencies, are associated with the performance of pilots. Airline pilots are trained in high levels of collaboration and team building. (Goeters, 2004). The reason for this emphasis is that effective intervention strategies to prevent conflicts are closely related to teamwork. Overall, research conducted by Ruff-Stahl et al. (2016) shows that it is possible to score entry-level student pilots on non-technical skills (NOTECHS), which was initially designed as a renewal assessment tool for trained airline pilots.

6. Conclusion

NOTECHS method provides clear and individually discernible results for each candidate, which can serve as an assessment of the individual's CRM ability. The clarity and transparency of the results regarding CRM capability make NOTECHS an easily understandable tool, even for non-psychologists. Therefore, this framework offers great usability to Human Resources personnel and airline pilots in the selection of their future colleagues. As a result of this research, a new model for personnel selection processes has been proposed for the aviation industry, one of the most risky and competitive sectors. This proposed model can be used in the pilot candidate selection processes of an aviation company operating in the aviation company and is also considered an important reference for flight schools and airline company managers. Furthermore, the model has the potential to be effectively utilized during Crew Resource Management (CRM) interview stages, providing a structured framework for assessing non-technical skills critical to aviation safety and operational efficiency.

7. Limitations and Future Directions for Research and Practice

This study evaluated the effectiveness of the Analytical Hierarchy Process (AHP) method in the selection process of pilot candidates. However, the study was limited to the pilot examiners in the assessment center of a specific airline company, which restricts the generalizability of the results. Future research should be conducted across different airlines and cultural contexts to enhance generalizability and should utilize more objective data collection methods such as observation and experimentation to mitigate participant bias. Given the AHP method relies on subjective judgments, combining it with other decision-making methods can reduce its limitations. Future studies should focus on evaluating both technical and non-technical skills in pilot selection processes and on assessing the long-term performance of selected candidates to compare the effectiveness of the selection processes. Research on the use of simulation technologies and artificial intelligence in pilot selection processes will help discover innovative and effective methods. Finally, investigating the effects of different cultural and psychological factors on the performance of pilot candidates will help optimize selection processes with cultural sensitivity. Future research conducted with these limitations and recommendations will contribute to a more scientific and effective selection process for airline pilot candidates.

Ethical approval

The studies involving human participants were reviewed and approved by the Istanbul University Research Ethics Committee (IUREC 356/2022). The participants provided their written informed consent to participate in this study.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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(NOTECHS)" conducted at Istanbul University, Business School, Department of Organizational Behavior. The authors gratefully acknowledge the invaluable contributions of Turkish Airlines Company Assessment Center throughout the doctoral research process.

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Innovative Contributions of Space Research to Other Sectors: Recommendations for Technology Policy Makers

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Abstract

Space research is not only limited to the development of space technologies, but also has the potential to provide innovative solutions to other sectors. This study examines how the technological advances achieved by space research can be transferred to various industries and the role of policy makers in this process. In particular, the innovative contributions of space technologies to strategic sectors such as energy, health, agriculture, communications and defence are discussed and concrete examples of the applicability of these technologies to other fields are presented. In this context, the study provides strategic recommendations for technology policy makers and underlines the necessary steps for sectoral transformation and sustainable growth. Technologies derived from space exploration offer effective solutions in a wide range of fields, from innovative materials to artificial intelligence, from robotic systems to data processing capacity. The study emphasises that policy makers should embrace these innovative solutions provided by space exploration and support sectoral adaptation processes. By creating regulations that encourage the transfer of innovative technologies, policy makers can strengthen cross-sectoral cooperation and accelerate the diffusion of new technologies. Moreover, the establishment of cooperation platforms between the public and private sectors can increase the sharing of technological know-how and contribute to the development of the innovation ecosystem.

1. Introduction

Space exploration, beyond increasing humanity's knowledge, is an important driving force in advanced technology development processes. Technologies developed to solve basic problems such as life in space, exploration and secure communication can find wide application in other sectors.

In innovation and technology transfer processes, the impact of space research on different sectors is increasing day by day (Silva et al., 2019). The challenging conditions encountered in space lead to the emergence of many innovative solutions, from durable materials to advanced data analysis techniques. These solutions not only contribute to the success of space missions, but also to industries on Earth (Neukart, 2024). For example, satellite technologies increase productivity in sectors such as agriculture and energy, while advanced imaging technologies used in medical research bring innovations to the health sector (Pesapane et al., 2018). Technologies developed in space exploration have the capacity to create major transformations in various industries on Earth. For example, solar panels used in the energy sector are a direct result of technologies developed in space (Bermudez-Garcia et al., 2021). Advanced imaging devices used in the healthcare sector were inspired by technologies developed during space exploration (Zang et al., 2015; Dastagiri and PV, 2020). In the field of agriculture, space-based satellite technologies are being used to increase productivity and promote sustainable agricultural practices (Martos et al., 2021). These innovative solutions show that space exploration is not only an exploration tool but also a source of innovation for the global economy.

The importance of space exploration is not only limited to discoveries, but also has the potential to provide innovative solutions that directly affect the welfare of societies. Technology-generating policy makers play an important role in the formulation of science and technology policies. These policies cover not only the acceleration of innovation and the development of new technologies, but also the transfer and application of these technologies to different sectors (Voulvoulis and Burgman, 2019). The successful transfer of innovations developed by space research to other sectors depends on the strategic moves of policy makers. Their task is to promote scientific research, support the innovation ecosystem and strengthen cross-sectoral cooperation (Shmeleva et al., 2021). In this context, it is important for policymakers to develop incentives and regulations to accelerate the integration process of space technologies into different sectors for sustainable growth and technological transformation.

In line with the above information, the main research question of this study is: 'While the technologies developed in space research offer innovative solutions in strategic sectors, what role should policy makers play in this process and how can they ensure the effective transfer of these technologies? 'This question emphasizes the applicability of space technologies on a sectoral basis and the importance of policy makers' strategic decisions in this process. By focusing on the innovative solutions provided by space exploration to other sectors, this study develops a unique perspective that provides strategic recommendations for policy makers who produce technology. While providing a new perspective on the economic and industrial impacts of space exploration on Earth, the study aims to be a guiding resource for sustainable development and sectoral transformation by examining the role of policy makers in this process in depth.

2. Technologies and Innovative Applications Used in Space Exploration

Space exploration has been at the forefront of technological advances, and many innovations have arisen from the need to overcome the harsh conditions of space. In particular, great progress has been made in areas such as durable materials sciences, advanced data processing techniques and energy generation. For example, the lightweight and strong materials used in spacecraft have started to be used in the aviation and automotive sectors (Gohardani et al., 2014). Experiments conducted in space have led to the development of new alloys and composite materials. For example, NASA's research on Titanium Aluminide has encouraged the use of lighter and more durable materials in the automotive and aerospace industry (Zhang et al., 2019). In addition, advanced sensor technologies and artificial intelligence play important roles in data analysis and operational processes in space exploration (Bi et al., 2022). Another important technology is the efficient use of solar energy. Making solar panels lighter, more durable and more efficient during space exploration has made great contributions to the energy sector on Earth (Verduci et al., 2022). For example, the solar panels used on NASA's Voyager 1 and 2 spacecraft were designed to withstand the harsh conditions in space. This technology is also used for solar power plants on the earth's surface and is constantly being improved to increase efficiency (Levchenko et al., 2018). The methods of obtaining electrical energy in space have offered new ways for sustainable energy sources on Earth, leading to significant developments, especially in the renewable energy sector. These technologies are widely used worldwide for clean energy production and carbon footprint reduction (Al-Shetwi, 2022).

Robotics and artificial intelligence technologies are another innovative area of space research. The remote control and autonomous operation of spacecraft and robots have inspired the integration of robotic systems, especially in industrial production, health and service sectors (Holland et al., 2021). These experiences gained from space technologies have paved the way for the rapid spread of automation and robotics. These systems, especially supported by artificial intelligence, enable more efficient and effective management of business processes (Pramod, 2022). The health sector has also gained significant innovations from space research. Medical devices and methods developed to solve the health problems faced by astronauts in space have been directly transferred to medical applications on earth. For example, advanced imaging techniques used in space research have initiated a new era in cancer treatment and diagnosis of neurological diseases (Scarpa et al., 2023). Moreover, tele-medicine applications and remote health services have emerged as a by-product of space research (Jeminson and Olabisi, 2021). Satellite technologies and global communication systems are one of the most common and effective technologies developed in space exploration. Many applications that affect our daily lives, such as GPS, weather forecasting and earth observation systems, are the result of space research (Yazıcı and Darıcı, 2019). The communication and information technologies sector also makes significant gains from space research. Satellite systems used in space have contributed to the expansion and improvement of communication networks worldwide. These technologies are used to increase internet access and accelerate global information flow, especially in developing countries (Rausser et al., 2023). The agricultural sector is another area that benefits from the integration of space technologies. Satellite technologies developed in space are used to increase agricultural productivity and manage natural resources more effectively. Satellite data used in agriculture are used to monitor weather conditions, analyze soil fertility and optimize crop management. This integration contributes to the dissemination of sustainable agricultural practices, especially among large agricultural producers and farmers (Kumar et al., 2024). Furthermore, data processing and artificial intelligence systems used in space exploration are an important source of sectoral solutions based on big data analysis. Finally, the defence sector has the potential to directly benefit from the technological advances offered by space exploration. Satellite-based security systems, robotic technologies developed during space exploration and artificial intelligence-based monitoring systems help to strengthen defence strategies (Rashid et al., 2023). These technologies can contribute to the reshaping of defence policies worldwide by offering new solutions in the field of national security.

2.1. The role of space technologies in sectoral transformation

Sustainable growth requires an approach that does not ignore environmental and social problems while ensuring economic development. In this context, space research helps to achieve sustainable growth targets by providing innovative solutions. Innovative solutions obtained from space technologies, especially in important areas such as renewable energy, water management and agriculture, contribute to the sustainable realization of economic development. In particular, experiments conducted in space have the potential to provide new materials and technologies to industries around the world. For example, materials science experiments conducted on the International Space Station (ISS) have enabled the development of more durable and efficient materials for solar panels. Thin film coating technologies tested in low gravity on the ISS have contributed to the production of longer-lasting and more efficient solar panels for the energy sector on Earth (NASA, 2018). Similarly, experiments in biotechnology in space have revolutionized the agricultural sector. The Veggie Project has not only improved the nutrition of astronauts through research on growing vegetables in space, but has also contributed to the development of agricultural techniques that are resilient to climate change around the world. Such experiments offer innovative solutions that make it possible to achieve higher yields with the use of limited water resources. In addition, high-fidelity water purification systems experiment in space have provided technologies that can be applied on Earth to increase access to clean water in developing countries. Water purification systems developed by NASA are now being used to provide clean drinking water in remote areas (NASA, 2013).

By supporting the integration of these innovations with other sectors, policy makers can accelerate the transformation of industry and pave the way for industrial innovation by providing productivity-enhancing solutions to many sectors with findings from space exploration. For example, organizations such as the European Space Agency (ESA) and the Japanese Space Agency (JAXA) continue to transform sectors such as energy, health and agriculture by sharing the results of experiments conducted in space (ESA, 2022).

The application of technologies obtained from space research in the field of renewable energy is one of the most important components of sustainable growth. In particular, solar energy panels and energy storage technologies have made great progress in space research and these technologies have become widespread on earth (Chel and Kaushik, 2018). For example, energy storage technologies, especially lithium-ion batteries, are important not only for individual users but also for energy infrastructure projects (Omer, 2008). Tesla's energy storage systems were developed to provide uninterrupted power in renewable energy production and increased energy supply security (Aşchilean et al., 2021). Similarly, energy storage systems used in smart grids in Japan have been effective in reducing carbon footprint by reducing fossil fuel consumption (Zhang et al., 2012). These technologies, inspired by battery management systems used in space exploration, make a great contribution to the energy sector. By developing policies that encourage such innovative energy solutions, policymakers can reduce dependence on fossil fuels and increase environmental sustainability. For example, the European Union's "Green Deal" program aims to expand energy storage technologies (European Commission, 2020).

Water management and agricultural technologies constitute another important dimension of sustainable growth. Advanced sensor technologies and satellite data used in space research are being used to increase productivity in agriculture and manage water resources more effectively (Abiri et al., 2023). Farmers in the USA optimize water use by analyzing soil moisture levels and crop growth with data provided by NASA's Landsat satellites (Zaussinger et al., 2019). In some countries in Africa, satellite imaging technology plays an important role in rural development projects (Oshri et al., 2018). These systems increase the productivity of agricultural lands and enable more effective management of water resources. By integrating such innovative solutions into rural development and agricultural policies, policy makers can contribute to solving global challenges such as food security and protection of water resources. For example, the European Space Agency's (ESA) Copernicus program uses satellite data to provide sustainable solutions in the agricultural sector (Schiavon et al., 2021).

Sustainable growth also includes social responsibility and community development goals. Medical devices and tele-medicine applications developed in space research improve healthcare services in rural and disadvantaged areas (Asi and Williams, 2018). By integrating such innovative health solutions into national health policies, policymakers can create a development model that extends to society at large. In this context, the application of space technologies for social benefit can strengthen the social dimension of sustainable development.

Space technologies attract attention with their ability to collect and analyze big data. Thanks to satellite systems, large amounts of data are obtained in areas such as transport, climate change and natural disaster management. These data support sectoral decision-making processes, enabling the development of more effective strategies (Sebestyén et al., 2021). By making regulations to increase the accessibility of space data, policy makers can encourage the use of these data by local businesses and research institutions. In this way, cross-sectoral collaborations are strengthened and innovative solutions can be realized more quickly.

The impact of space technologies on sectoral transformation also manifests itself in the field of labor and employment. Space research leads to the emergence of new professions and specializations (Cooke, 2004). Policy makers should develop training programes and employment policies to support this change. The creation of new occupational fields related to space technologies encourages young generations to turn towards this field and increases the qualifications of the labor force. In this way, it is possible to provide qualified labor force and increase job opportunities in sectoral transformation processes. Space technologies can serve as a catalyst for transformation not only in its own field but also in many other sectors.

2.2. Challenges encountered in the innovation process and solutions

Many challenges are encountered in the process of applying space technologies in other sectors. One of these challenges is the complex nature of space technologies. An appropriate framework needs to be established to integrate space-derived data into specific industries. To overcome this complexity, policy makers should develop legislation that encourages standardization and harmonization processes. Thus, the integration of space technologies can be realized more smoothly.

Another challenge in the innovation process is the lack of financing. Space technologies are often mega projects that require high costs, making it difficult for private sector players to invest (Denis et al., 2020). Policy makers can facilitate the financing of such projects by encouraging public-private partnerships. They can also support innovative projects by establishing funding programes for space technologies.

Lack of training and expertise is also an important obstacle in innovation processes. Professionals with the necessary know-how are needed for the application of space technologies in other sectors (Arciénaga Morales et al., 2018). Therefore, policy makers should increase the qualified workforce by improving education programes related to space technologies. They can also accelerate the flow of knowledge in the sector by establishing collaborations with universities and research institutions.

Technological harmonisation and integration problems are also one of the obstacles to the innovation process. Existing systems in different sectors need to be harmonised with space technologies (Shirowzhan et al., 2020). For example, the integration of energy storage technologies developed in space research into existing electricity grids around the world poses serious technical challenges. Sectoral cooperation and standardisation efforts are of great importance for solving such problems. Policy makers can facilitate integration processes by encouraging sectoral cooperation. For example, the European Union's Horizon Europe programme is developing multi-stakeholder projects to support the integration of space technologies with the energy and agriculture sectors (European Commission, 2021).

Financial challenges are another major barrier to the implementation of space technologies. Space research and development processes often require large investments, which can take time to translate into commercial applications. For example, SpaceX's development of reusable rocket technology was carried out at great cost, but the economic benefits of this technology only emerged in the long term. Therefore, public-private partnerships should be encouraged, consultancy services and technical support mechanisms should be established to accelerate technology transfer processes and reduce the financial burden (Vance, 2017).

Legal and regulatory barriers are also among the other major challenges faced in the implementation of space technologies. In particular, data sharing and intellectual property rights cause significant problems in this process. For example, national and international laws regulating civilian use of satellite data sometimes restrict the use of these technologies in critical areas such as agriculture and water management. In India, satellite data-based agricultural applications developed by ISRO (Indian Space Research Organisation) were initially used on a limited scale due to regulatory issues (OECD, 2020).

To address such regulatory issues, policy makers can work with sectoral actors to develop more flexible and inclusive regulations. For example, the NASA Technology Transfer Programme in the US has allowed the private sector to adopt technologies developed in space exploration more rapidly by relaxing legal regulations (NASA, 2020).

In conclusion, technological adaptation, lack of financial resources and legal regulations are the main challenges faced in the implementation of space technologies. In order to overcome these obstacles, sectoral cooperation needs to be strengthened, advisory and technical support mechanisms need to be established, and more flexible regulatory frameworks need to be adopted. An active role of policy makers in these processes will ensure that the benefits derived from space technologies reach a wider audience.

2.3. Transferring lessons learnt from the space ecosystem to other sectors

Lessons learnt from the space ecosystem constitute an important resource for innovative applications in other sectors. The experiences offered in areas such as space research, system integration, data management and co-operation inspire sectoral applications. Especially in data analytics and big data management, the space sector offers solutions that can be applied in many areas. The adoption of these experiences by other sectors can accelerate innovation processes. The cooperation and partnership model offered by the space ecosystem can also be a valid strategy for other sectors. Since public and private sector co-operation is of great importance in space research, this model can also be applied in sectors such as energy, health and agriculture to encourage knowledge and resource sharing. Policy makers can contribute to the strengthening of sectoral co-operation by making regulations that support such co-operation.

Lessons from the space ecosystem are also valuable in the field of process management and project management. Space projects are managed under tight timelines and budget constraints. Other sectors can improve the effectiveness of their projects by adopting management strategies from these projects (Garon, 2006). Policy makers can provide guidance documents and guidelines for sectors to adopt such strategies.

The challenges faced in space exploration and their solutions can be applied to other sectors. In particular, difficulties in technology transfer and innovation processes can be overcome by learning from the experiences in the space sector (Shmeleva et al., 2021). Policy makers can organize platforms and workshops to share these experiences. Such events can encourage innovation by increasing knowledge exchange between different sectors. The sustainability-oriented approach of the space ecosystem can set an example for other sectors. Space exploration offers important lessons on environmental sustainability and resource management. Adopting these lessons can contribute to the development of sustainable practices in sectors such as energy and agriculture. Policy makers can help sectors to reduce their environmental impacts by making regulations that encourage these sustainable practices.

2.4. International co-operation and coordination among policy makers

Space research is an important field that encourages international co-operation. Countries share their experiences in space technologies, develop joint projects and ensure the flow of information. In this context, international co-operation plays a key role for the integration of space technologies into other sectors. Policy makers can benefit from the experiences of different countries by making arrangements to increase co-operation in international platforms.

International co-operation encourages the sharing of knowledge and experience. Co-ordination between countries enables different approaches to come together to identify best practices. Policy makers help this process to become more efficient by creating appropriate platforms for international cooperation (Bull and McNeill, 2019). In particular, collaborative efforts that support the integration of space technologies into other sectors can stimulate sectoral innovations.

Coordination among policymakers is an important factor in transferring knowledge gained in space research to other sectors. Policy makers from different countries coming together to develop common strategies can accelerate sectoral transformation processes (Stone et al., 2020). Such coordination can facilitate the adoption and implementation of space technologies and provide more effective solutions at the global level. International co-operation and co-ordination support the implementation of sustainable solutions obtained in space research in other sectors. Space technologies can promote sustainable development by providing solutions to environmental challenges. Policy makers can ensure the dissemination of these solutions through international co-operation. Thus, the social and environmental benefits of space exploration can be increased.

3. The Importance of Co-Operation in International Space Research and Technology Transfer

Cooperation in international space research and technology transfer plays an important role in accelerating the scientific and technological progress of countries around the world. Since space exploration is a complex and costly project, different countries need to pool their knowledge, resources and experience. These collaborations allow each country to achieve more effective and efficient results by combining its own capabilities and areas of expertise. This encourages innovation not only in space research but also in other scientific disciplines around the world.

Another important aspect of international co-operation is that it increases knowledge sharing. Researchers and experts from different countries, working on space projects, have the opportunity to benefit from each other's knowledge and experience. Such interactions accelerate innovation processes and pave the way for new ideas (Wulf and Butel, 2017). For example, international organizations such as the European Space Agency (ESA) and NASA collaborate on large data sets, experimental findings and technological innovations through joint projects (Adams, 2019). Such collaborations enable the advancement of space research at a global level, while at the same time increasing synergy in the scientific community. Furthermore, co-operation in international space exploration helps to use resources more efficiently. Since space missions are often costly, many countries can share this financial burden by pooling their resources. This contributes to making space exploration more sustainable (Gao and Chien, 2017). For example, the International Space Station (ISS) project demonstrates the endeavor of different countries to come together to achieve common goals. Such projects strengthen not only space research but also international relations (Stewart and Dittmer, 2023). International co-operation also contributes to the development of skills in science and technology. The exchange of knowledge and experience between countries offers new opportunities to young researchers and scientists (Standke, 2006). Such collaborations can be supported by training programmes, internship opportunities and joint research projects. By encouraging international collaborations, policy makers can contribute to the career development of scientists and thus increase the human resource potential in space research.

Cooperation in international space research and technology transfer promotes a culture of peace and co-operation. The co-operation of different countries in the field of space not only achieves scientific and technological goals, but also increases solidarity and understanding in the international community. Such cooperation emphasizes the importance of cooperation in solving international problems and builds trust between countries. Therefore, cooperation in international space research and technology transfer is an important element that promotes not only scientific progress but also global peace and co-operation.

4. The Importance of Co-Operation in International Space Research and Technology Transfer

In a global competitive environment, space research and technology transfer play an important role in the scientific and technological development of countries. This competition creates an accelerating effect in the development of space technologies. Countries try to gain competitive advantage in the global market by accelerating technological innovations through international co-operation. In this context, it is of great importance for policy makers to make arrangements to support innovative projects.

Competition in space research encourages the sharing of scientific knowledge and technology. Countries can utilize their resources more effectively by cooperating in certain areas. For example, joint projects in space bring together the knowledge and experience of scientists and engineers to produce innovative solutions (Rausser, 2023). Policy makers should develop funding mechanisms and incentives to support such joint projects.

In order to accelerate technological innovations in a global competitive environment, education and human resource development is also a critical factor. Countries should offer training programes and scholarships to increase the qualified workforce in the field of space technologies. In this way, young generations are encouraged to be interested in space research, while increasing the expertise in the sector (Zickafoose et al., 2024). In this process, policy makers can strengthen education programes in cooperation with the private sector and academic institutions.

In addition, collaborations between countries facilitate technology transfer in a global competitive environment. International collaborations in the development of space technologies bring together the expertise and experience of different countries. This enables the development of innovative solutions more rapidly (Pandey et al., 2022). By encouraging such collaborations, policymakers can increase competitiveness at the international level. Supporting innovation in a global competitive environment is the responsibility of policymakers. In order to accelerate technological innovations, policymakers should develop policies that encourage R&D investments. In addition, they can accelerate technological developments by creating support programs for innovative initiatives. In this way, competitiveness in the field of space research and technology transfer can be increased and sustainable growth can be achieved.

5. Conclusion

This study examines the innovative contributions of space research to other sectors and how technology policymakers can benefit from these contributions. The benefits provided by space technologies in various fields such as energy, health, agriculture, defense and communication show that these technologies are not limited to space exploration alone, but also have a significant impact on many sectors around the world. This situation reveals that space research has a strategic importance and emphasizes the need for policymakers to increase investments in this field.

Space research is considered an important resource in the search for solutions to global problems with its long-term contributions to environmental sustainability, data management and innovative solutions. In particular, the integration of remote sensing and communication technologies ensures that applications in different sectors become more efficient. In addition, supporting space research through international collaborations increases knowledge sharing and accelerates innovation processes between countries. In this context, encouraging collaborations in the space field by policymakers will support both scientific developments and economic growth. The strategies suggested for policymakers provide a roadmap to develop the applications of space research in other sectors. Regulations to be made in the fields of education, research and investment will ensure that space technologies reach a wider audience, while also increasing the role of these technologies in producing innovative solutions. In particular, the creation of educational programs and career opportunities for young generations will strengthen the human resources in this field and contribute to future space projects. As a result, the opportunities offered by space research are not limited to space exploration alone, but also make significant contributions to innovation processes in many sectors.

6. Discussion

This study examines the innovative contributions that space exploration brings to different sectors and how these contributions can be evaluated by technology development policy makers. In particular, the role of these technological achievements in increasing efficiency, sustainability and competitiveness in various sectors is noteworthy. The study aims to provide strategic recommendations on how policy makers can use these contributions more effectively. For example, Victor et al. (2024) emphasized the potential of remote sensing technologies to increase efficiency in agriculture and showed that the data support provided by these technologies to farmers makes significant contributions to sustainable agricultural practices. Similarly, Zohrehvandi et al. (2020) stated that data obtained from space is important for resource management in the energy sector. Such findings reveal that the applications of space exploration in different sectors require not only a technical but also a strategic approach.

The effects of space exploration on the health sector are also remarkable. A study by Shirah et al. (2023) examined how experiments conducted in space contribute to the development of remote health services. Such studies show how critical the innovative solutions offered by space technologies in the field of health are in terms of access to health services, especially in rural and hard-to-access areas. In this context, it is obvious that technology policy makers need to develop strategic plans to maximize the potential of space research in the field of health.

At the same time, studies on the economic and social impacts of space research also provide important results. Pyka (2017) emphasized the positive effects of space technologies on economic development and explained the role of these technologies in sectoral transformation in terms of employment, new business opportunities and innovative solutions. At this point, it is concluded that policy makers should increase their investments in space research and support cooperation in this field. In addition, encouraging international cooperation will contribute not only to information sharing but also to the acceleration of technological innovations at the global level.

Discussions in the existing literature on the application areas and potential benefits of space research also reveal some difficulties. For example, the obstacles encountered in technological integration processes and the effective management of resources constitute a significant obstacle to the application of space research in other sectors (Hew and Brush, 2007). Therefore, it is of great importance for technology policy makers to develop strategies to overcome these difficulties and encourage sectoral cooperation. In order to increase the applicability of space technologies and to make the most of these technologies, policy makers need to develop innovative solutions in collaboration with relevant stakeholders. As a result, the innovative contributions of space research to other sectors are discussed in a wide range in the existing literature. However, in order to make the best use of these contributions, technology-producing policy makers need to encourage sectoral collaborations and develop strategic plans. Space research should be considered not only as a scientific discipline but also as an important tool for social and economic development, and this potential should be maximized.

7. Recommendations

7.1. Recommendations for increasing coordination among policy makers

International space research and technology transfer is a complex and multi-stakeholder process. In this process, effective coordination between policy makers from different countries increases the efficiency of cooperation. Policy makers can encourage the sharing of experience and knowledge by organizing regular meetings and conferences. Such events strengthen relations between countries and help develop a common understanding of different aspects of space research. In addition, it is important to establish an effective communication network among policy makers. This network makes it easier to follow current developments in space technologies and research. Social media and digital platforms, in particular, can increase cooperation opportunities by providing a rapid flow of information. Effective use of these platforms by policy makers can strengthen coordination and cooperation. Common goals need to be determined in order to encourage international cooperation. Policy makers can develop common strategies on these issues by determining the areas and goals to be cooperated in space research. Common goals ensure that cooperation is carried out in a more structured manner. In this context, issues such as sustainable development in space, solving environmental problems and scientific research can be determined as common goals.

Policymakers' arrangements that support the sharing of technological developments will also increase coordination. Such arrangements facilitate the transfer of knowledge and technology between countries, further strengthening cooperation. For example, simplifying the licensing and patent processes related to the use of certain space technologies can pave the way for international cooperation. In this way, interaction between countries will increase, and innovative solutions in space research can be implemented more quickly. It is important to increase transparency in international space cooperation. Policymakers should conduct cooperation processes in a transparent manner and inform the public about these processes. Transparency contributes to the creation of an environment of trust and increases the trust that countries have in each other. This trust is a critical factor for the success of international cooperation. By adhering to the principle of transparency, policymakers can make international space research cooperation more effective.

7.2. Recommendations for cross-sectoral collaborations

Policy makers should prioritize the establishment of frameworks that foster cross-sectoral collaborations between space research and industries such as healthcare, energy, agriculture, and telecommunications. These collaborations should be driven by shared goals, such as enhancing sustainability, improving resource management, and accelerating technological advancements. By aligning space technologies with the needs of other sectors, policy makers can create mutually beneficial partnerships that not only promote innovation but also ensure the practical application of space-derived solutions in solving global challenges. This can be achieved through targeted incentives, funding mechanisms, and the development of multi-disciplinary platforms that encourage dialogue and idea exchange across sectors. Such collaborations will unlock new opportunities, driving innovation and contributing to the broader goal of sustainable economic growth.

Additionally, policy makers should encourage the development of public-private partnerships (PPPs) to facilitate the integration of space research outputs into diverse sectors. These partnerships can provide the financial and technical resources necessary to bring space-derived technologies to market quickly. Policymakers can create policies that offer incentives for private sector investment in space-related innovations while ensuring that the benefits of these technologies are distributed across sectors. By establishing clear, supportive regulations and frameworks for collaboration, policy makers can facilitate seamless interactions between public research institutions and private industry, accelerating the adoption of innovative solutions. This approach not only strengthens the economic and technological resilience of various sectors but also enhances the global competitiveness of industries involved in space research and technology transfer.

7.3. Recommendations for future policy development processes

In order to ensure the continuity of the contributions of space research to other sectors, there are a number of recommendations that should be taken into consideration in future policy development processes. First, investments in research and development activities of space technologies should be increased. Policymakers can ensure that innovative projects are implemented by creating funding mechanisms that encourage investments in this field. Investments in space research will positively affect not only the space industry but also other related sectors.

Second, training and awareness programs should be developed for the integration of space technologies into other sectors. Policymakers can encourage businesses to benefit from the potential of these technologies by organizing training on how to use space technologies. Training programs will facilitate access to space technologies, especially for small and medium-sized enterprises, and increase their competence in this field.

Thirdly, encouraging international cooperation stands out as an important strategy. In future policy development processes, strategies should be developed to strengthen cooperation with different countries and increase knowledge sharing. Such collaborations will ensure that innovative solutions obtained in space research reach a wider audience. In this context, policymakers should develop policies that encourage participation in international projects.

Fourthly, public participation should be encouraged in order to increase the social benefits of space research. Policymakers should organize campaigns that inform the public about the effects of space research on society and encourage their participation. In this way, public interest in space research can be increased and awareness in this area can be increased. Public participation will help the benefits provided by space research reach a wider audience. Policymakers need to adopt a flexible and adaptable policy development process. Rapid developments in space technologies and research can affect policy development processes. Therefore, policymakers should constantly monitor developments and update their policies when necessary. A flexible policy framework will facilitate the integration of space research with other sectors and enable the implementation of innovative solutions.

7.4. Strategic recommendations for policy makers

Technology policymakers should develop a strategic approach to maximize the benefits of innovative solutions offered by space research. First of all, policymakers should create a strong technology transfer ecosystem to support the integration of technologies developed in space research into the local economy. This will ensure rapid dissemination of innovation and its effective use in other sectors. In addition, cooperation between local manufacturers and research institutions should be encouraged.

Another strategic recommendation is to increase state-supported research and development (R&D) activities. The cost of space research is generally high, but the return on this cost can be more than offset by technological contributions provided to other sectors. By increasing R&D investments, policymakers can ensure the spread of space research to wider sectors and enable faster commercialization of innovative solutions. Public-private partnerships in particular offer great opportunities in this area.

Integrating technological gains from space research into sustainable development goals should be another priority for policymakers. Renewable energy technologies developed in space, solutions that increase agricultural productivity, and applications that improve health systems are critical for a sustainable future. Policymakers should develop long-term strategies on how to use these technologies in line with sustainable development goals.

Education and talent development should be another focus of policymakers. In order to fully benefit from the technological solutions offered by space research, an expert and qualified workforce is needed. Policymakers can accelerate the technology transfer process by supporting education programs and talent development projects in this field. In addition, the orientation of young generations to space technologies and other innovative areas should be encouraged. Policymakers can ensure that the gains from space research are disseminated on a global scale by increasing international cooperation and knowledge sharing. Space research is generally a study that transcends borders and has global impacts. Therefore, cooperation should be developed in the international arena to ensure that technologies obtained from space research are shared and implemented among different countries.

7.5. Recommendations for future policy development processes

Space research provides long-term innovative contributions, thus presenting important strategic implications for technology policy makers. In this context, the development of space technologies ensures integration with other sectors and thus supports economic growth. The efficiency gains and cost reductions achieved in space research can serve as an example for other industries. This situation provides an opportunity for policy makers to develop strategies that support and encourage space research.

The results of space research can be a source of inspiration for innovative solutions in various industries. For example, the applications of materials and technologies used in space in sectors such as health, energy and communication provide competitive advantages to local industries. Policy makers can increase the competitiveness of local businesses by adopting such innovative solutions. Therefore, the knowledge and technologies obtained from space research should be considered as a strategic resource.

The integration of the results of space research into other sectors also plays an important role in achieving sustainable development goals. For example, space technologies can be applied in areas such as environmental monitoring, agricultural productivity and natural disaster management. By encouraging the use of such technologies, policymakers can both find solutions to environmental problems and support economic development. Therefore, there is a strong link between space research and sustainable development.

The long-term innovative contributions provided by space research also encourage international collaborations. Technology-producing policymakers can increase the sharing of knowledge and experience by establishing collaborations with different countries. This allows for the acceleration of innovation at the global level and the development of more effective solutions. Supporting these collaborations by policymakers strengthens.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Multirotor Unmanned Aerial Vehicle Systems: An In-Depth Analysis of Hardware, Software, And Communication Systems

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Abstract

This paper presents a comprehensive overview of multirotor unmanned aerial vehicle (UAV) systems, focusing on the mechanical integration of quadcopters. The rapid advancement and widespread adoption of UAVs have established them as a significant research and development field. This review examines the key components and technologies in UAV design and operation, including frame types, flight control boards, motors, electronic speed controllers, batteries, propellers, communication systems, and software. It analyzes various frame materials and configurations, detailing their advantages and limitations. The paper examines the essential role of flight control boards and inertial measurement units in maintaining stability and enabling autonomous flight. It explores motors, propellers, and power systems selection criteria and characteristics in detail. The review evaluates UAV communication technologies, including radio frequency, WIFI, Bluetooth, and infrared, comparing their capabilities and limitations. It also covers autopilot software and ground control stations for mission planning and execution. This comprehensive analysis serves as a valuable resource for researchers, engineers, and enthusiasts working with design, development, and application of multirotor UAV systems.

1. Introduction

With the development of societies, the importance of manpower and the increase in the value given to human beings have led to the reduction of the manpower directly used in technology. In this way, it has been ensured that people are isolated directly from risky tasks and the system is separated from human control. New technologies in this field are being developed every day. In this context, systems that do not have 'human' on board are called unmanned vehicles. Unmanned vehicles are expected to meet the following requirements: remote control capability and autonomous decision-making functionality.

Unmanned vehicles are divided into different types according to their areas of use. Some of these are Unmanned Aerial Vehicles (UAV), Unmanned Surface Vehicles, and Unmanned Underwater Vehicles (Wibisono et al., 2023). There are three main categories of unmanned aerial vehicles, which include low-altitude platforms known as LAPs, high-altitude platforms known as HAPs, and satellites. This work concentrates on UAV-enabled mobile edge computing, therefore UAVs are examined from multiple perspectives (Yazid et al., 2021). **Error! Reference source not found.** presents a classification of LAP-type UAVs based on their design characteristics, physical dimensions, operational range, and rotor configuration (Yazid et al., 2021).

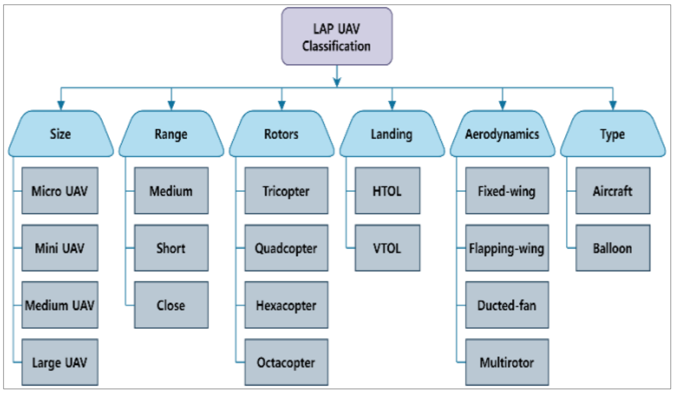

Figure 1. Classification of LAP UAVs.

Multicopters are aerial devices with more than two motors, controlled through yaw, roll, pitch, and lift solely by adjusting speed (rpm). Electro-mechanical sensors and computational devices provide stabilization. They are classified by their propeller count, including tricopter, quadcopter, hexacopter and octocopter (G. Özdoğan and K. Leblebicioğlu, 2022; Özen and Oktay, 2022). Quadcopter designs have emerged as the most common multicopter (Quan, 2017). The term drone, meaning male bee is another widely used name (Metz and Tarpy, 2022; Ural Bayrak et al., 2022). A UAV describes an unmanned vehicle operated remotely or autonomously without any onboard pilot or crew (Mohsan et al., 2022; Özen and

Oktay, 2024). UAVs have gained popularity due to decreasing costs of electronic components including microcontrollers, sensors, and lithium-based batteries. Open-source systems offer universities and enthusiasts low-cost software and hardware modifications options for UAVs (S. Rezwan and W. Choi, 2022). The UAV industry maintains significant growth, with market projections showing expansion from US $30.6 billion in 2022 to US $55.8 billion by 2030, at a Compound Annual Growth Rate (CAGR) of 7.8% (Y. Bai et al., 2023).

The United States hods the most share of investment in UAVs. The number of UAVs pilots trained surpassed the number of jet pilots trained per year in the United States since 2015. It is predicted that there will be 30,000 UAVs in the skies by 2030 (McKelvey et al., 2019). As of May 2022, the Federal Aviation Administration (FAA) in the United States reported significant UAV adoption, with 855,860 registered drones and 277,845 issued remote pilot licenses. These figures demonstrate the substantial integration of UAV technology into both recreational and commercial sectors across the country (Studiawan et al., 2023).

UAVs can be divided into 3 main groups: rotary wing, fixed wing and hybrid (Çelebi and Cengiz, 2024; Velusamy et al., 2022). Fixed-wing UAVs maintain lift through stationary and immobile. Their ability capability depends on the continuous forward motion of the fuselage, powered by either an internal combustion engine or an electric motor. These typically single-engine vehicles offer lower production costs compared to other UAV types. While fixed-wing UAVs require large areas for landing and take-off, they excel in long-range flight capabilities (Kuzu, 2018).

Rotary-wing UAVs uses propellers rotating counter to gravity to maintain lift. In rotary-wing UAVs, the fuselage remains stationary while the wings rotate, eliminating the need for forward motion. As a result, the movements of rotary-wing UAVs in the air are more controlled, allowing them to hover and perform takeoff and landing in small spaces. Due to the increased number of motors, motor controllers and batteries depending on the number of rotor blades, the production costs are higher compared to fixed-wing UAVs. Rotary-wing UAVs have shorter flight ranges. Hybrid UAVs are designed to harness the advantages of both rotary-wing and fixed-wing UAVs (Çabuk and Yıldırım, 2021, 2021; Genç et al., 2008; Kuzu, 2018).

For an object heavier than air, like an airplane, to fly, lift force is required (Gülçat, 2010). The main source of this lift is the airflow over the surfaces of the plane due to the thrust generated by the aircraft's engine and the speed the plane gains (Genç et al., 2008). To turn a multicopter in the desired direction, a positive torque must be applied. This is achieved by adjusting the torque of each motor. The torque effect is observed by changing the motor rotation speed. During hover, the applied torque is zero. To turn left or right, each motor must adjust their speeds accordingly. Reducing motor speed decreases thrust. Speed changes alter the thrust force applied by the motor. During quick rotation, the device may lose altitude. To maintain altitude while rotating, some motors must increase speed to compensate for the reduced thrust from slower motors (Kılıç, 2014).

Modern UAVs find applications across multiple sectors, primarily in military activities (intelligence gathering, border control, enemy detection, ammunition transport), and civilian fields such as energy (fault detection and gas measurements), agricultural applications (data collection), map-making, documentation of archaeological sites, forestry applications, and disaster management. Ongoing research and development continues to expand UAV applications in areas such as first aid (search and rescue) and traffic monitoring (road conditions) (Yürek, 2018). The wide range of UAV applications is presented in Table 1 (Çetin, 2019; Yürek, 2018).

Table 1. UAV application areas.

Field	Sub-application Areas
Agriculture and forestry	Crops and plants, trees, forests, soils, vegetation cover and plant growth
Atmospheric	Observation, and weather analysis and pollution
Military	Intelligence, border control and ammunition transport
Cultural	Protection of historical sites and archaeological studies
Environmental monitoring	Volcanic studies, soil, water environments, drainage, and rural roads and geological infrastructure
Logistics	Cargo
Disaster monitoring	Hurricane, typhoon, tornado, earthquake, fire, nuclear leak, waste detection, flood, avalanche and landslide epidemics
Photogrammetry	Digital elevation model and 3d mapping, mosaics, orthophotos, and rectification, measurements and cadastral applications
Urban	Supervision, monitoring, road information, urban planning, building façade analysis and
	City land use
Wildlife	Fauna and flora

Research interest in UAVs technology continues to grow worldwide, driven by successful projects successful projects. Like traditional helicopters, quadcopters can hover in the air. Quadcopters combine the advantages of vertical flight vehicles, hovering capability and horizontal flight vehicles. They also provide advantages with improved stability and simpler design compared to conventional aircraft. A quadcopter has four rotors: two rotate clockwise, and the other two rotate counterclockwise, enabling flight. This configuration allows for smaller propellers, which store insignificant amounts of kinetic energy, thus reducing potential damage during operation (Carvalho, 2013; Çetinsoy et al., 2008). The versatile design options of four-rotor UAVs enable researchers to achieve diverse technical specifications.

Although increasing a multicopter's flight range through using a higher capacity battery is possible, the extra weight from the larger battery limits the flight time. Multicopter propellers force air to flow downward to generate thrust (Başaran, 2017). The reaction of the wings to the air is quite important. The propeller affects the thrust force, flight speed, maneuverability, and flight stability of the multicopter (Hell et al., 2018).

While several academic surveys exist in the literature on multirotor UAVs (B B V L and Singh, 2016; Chen et al., 2023; Fu et al., 2019; Magnussen et al., 2014), they primarily focus on optimization parameters like control systems and trajectory generation, with only limited coverage of hardware components (Borah et al., 2016; Seidu et al., 2024). Notably, these studies lack comprehensive analysis of software and communication systems. This paper addresses this gap by providing a thorough overview of multirotor UAV systems, with particular emphasis on the mechanical integration of quadcopters. The study begins with a detailed analysis of hardware components, including frame types, flight control board specifications, motor characteristics, electronic speed controller parameters, and propeller and their selection criteria. Following this, the paper examines software systems, covering autopilot software platforms, ground control station implementations used for mission planning and execution tools. The final section explores communication technologies, discussing radio frequency systems, WIFI capabilities, Bluetooth integration, and infrared communication, along with a comparative analysis of their advantages and limitations. This comprehensive examination of components and systems serves as an essential reference for researchers, engineers, and UAV enthusiasts engaged in the design, development, and application of multirotor UAV systems.

2. UAV Hardware

UAVs come in various shapes and sizes. Despite their different configurations, the fundamental components remain the same. These include the controller, motor, battery and charger, propeller, motor driver, frame, flight controller, and power distribution. Advanced models may incorporate video cameras, Global Positioning System (GPS), compass, barometer, sonar sensors, autonomous flight capabilities, and telemetry. Most UAVs also integrate a gyro and accelerometer with their sensors (Kılıç, 2014; Kutlu, 2019; Öngül, 2017). Figure 1 shows a connection diagram of a rotary-wing UAV (Pala, 2018).

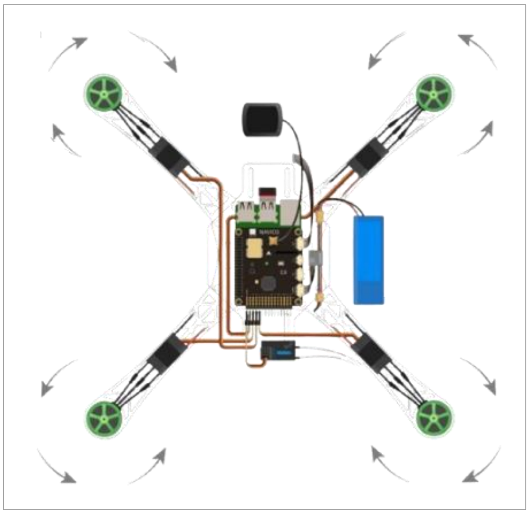

Figure 1. A connection diagram of a rotary-wing UAV.

2.1. Frame

The multicopter frame, also known as the body, is the skeleton of the UAV. The fundamental forces acting on the frame are gravity and air pressure.

2.1.1. Frame materials

Common materials for UAV frames include aluminum, wood, plastic, fiber glass, and carbon fiber (Elmeseiry et al., 2021). When considering the frame, it is essential to choose a material that is both lightweight and durable. The strengths and weaknesses of these materials are as follows:

a) **Wood:** A wooden frame is often used in such projects due to its low cost and light weight. However, wooden frames are significantly affected by weather conditions and are prone to breaking and warping. Additionally, mounting other components on a wooden frame can be challenging. Screws and other fasteners mounted on a wooden surface are likely to deform the holes if removed and reinstalled multiple times or if the wood warps (Altın, 2013).

b) **Carbon fiber:** Carbon fiber is an excellent material for UAV frames as it handles stress and deformation better than wood and is lighter than aluminum. However, it is not commonly chosen due to its difficulty in procurement and challenges with repair and maintenance (Altın, 2013).

c) **Aluminum:** While aluminum is widely used in modern UAV applications, its weight limitations lead manufacturers to seek alternative materials (Hairi et al., 2023).

2.2. Frame types

UAVs use three fundamental frame configurations for quadcopter:+-type, H-type and X-type (Peksa and Mamchur, 2024). Figure 2 shows the different quadrotor frame types: a) cross-shaped frame, b) H-shaped frame and c) plus-shaped frame.

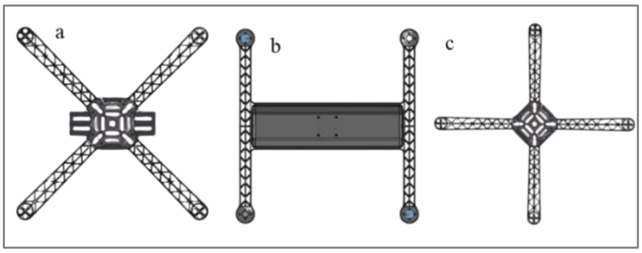

Figure 2. Quadrotor frame types: a) cross-shaped frame, b) H-shaped frame and c) plus-shaped frame.

a) **Cross-shaped frame:** X-type frame provides a more stable and easily manageable system during the construction. This feature drove early quadcopter design. The design requires less effort in controller system development because moments are equal on all axes, and the center of gravity is centralized. During pitch or roll movements, X-type quadcopters apply equal moments since the distances of the motors from the center axis are the same. The frame also enables a clearer field of view when capturing images (Kılıç, 2014).

b) **H-shaped frame:** This newer frame type offers durability and more space for additional payloads, benefiting users. However, H-type quadcopters face challenges with forces acting on the center of gravity can cause issues. To maintain consistent pitch and roll angles at the same angular velocity, equal moment values must be created. Consequently, during turns, motors farther from the rotation axis require more thrust, complicating the controller design (Batmaz, 2013).

c) **Plus-shaped frame**: The plus (+) frame configuration delivers enhanced maneuverability and control characteristics. However, this design concentrates impact force on a single arm during crashes (Al-Haddad et al., 2024). Some researchers further classify this frame type into X variations (D. A. Gandhi and M. Ghosal, 2018).

The primary difference between X-shaped and H-shaped designs is the varying forces applied to the motors during orientation changes. In static and steady positions, the forces applied to all motors in both X-shaped and H-shaped quadcopters are approximately the same.

2.3. Flight control board

This unit functions as the brain of the system, performing critical functions such as maintaining balance, reading control data, and battery monitoring. It is the most critical part of the system (Peksa and Mamchur, 2024). The flight controller in a UAV is typically an integrated circuit consisting of a microprocessor, sensors, and input/output pins. Flight control boards require parameter adjustments in the flight control software because they are not programmed to operate specific UAV types or configurations (Pala, 2018). The board calculates required motor speeds to meet user-desired movements and sends signals to the motors. It determines various criteria such as motor accelerations and target speeds and ensures quadcopter stability through angle and acceleration sensors. The system includes predefined scenarios for emergencies. For instance, some boards can return to the initial takeoff height and position when battery levels drop below critical levels. Some flight boards feature autonomous navigation on pre-programmed routes without user input. These boards include autonomous flight capabilities (Öngül, 2017). Figure 3 shows an illustration of a flight control board.

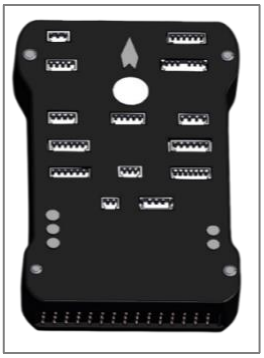

Figure 3. An illustration of a flight control board.

The first task of the flight control board is to receive data from the inertial measurement unit (IMU). The data produced by the IMU reaches the flight control board through various communication channels (Neumann and Bartholmai, 2015). These include protocols such as SPI, UART and I2C, or analog data transmission. The flight control board must receive this data for processing from the IMU (Podhradsky, 2012).

Common flight controller functions include (Kılıç, 2014):

a) **Gyrostabilization:** Helps keep the device stable and under the pilot's control.
b) **Self-leveling**: Keeps the device stable in the air when the controller is released.
c) **Carefree**: Allows the device to be controlled according to its original orientation, even if its direction changes.
d) **Altitude hold:** Allows the device to maintain a specific distance from the ground without adjusting the throttle.
e) **Position hold:** Allows the device to hover at a specific location in the air.
f) **Return home:** Automatically makes the device land back at the takeoff point.
g) **Waypoint navigation:** Allows the device to follow predetermined points.

Controlling a quadcopter requires more complexity compared to airplanes. The flight controller manages the quadcopter using various sensors and telemetry systems. A flight control board may include accelerometers, gyroscopes, barometers, temperature sensors, current sensors, compasses, GPS circuits, voltage sensors, data recording elements, and OSD (On-Screen Display). These components can be external but maintain communication with the board. Flight controllers ensure stable flight and adjust motor speeds for various maneuvers (Elmas, 2019; Pala, 2018).

The basic sensor modules in the flight card are gyroscope, accelerometer, barometer and compass. Additional hardware like GPS modules, anemometers, and infrared sensors can enhance functionality and enable more precise flight.

2.3.1. Inertial measurement unit

The IMU is an electronic system embedded within the flight control board that measures the roll, pitch, and yaw angles of the aircraft (Tomaszewski et al., 2017). An IMU has degrees of freedom based on its data inputs and measurement axes. It primarily consists of an accelerometer and a gyroscope. Most IMUs combine a three-axis accelerometer and a three-axis gyroscope, creating a 6 Degrees of Freedom (6-DOF) IMU (Henderson et al., 2021). IMUs offer advantages over separate gyroscopes and accelerometers in managing measurement accuracy factors like drift and bias. Some IMUs incorporate a three-axis magnetometer, achieving 9 DoF. Adding a pressure sensor creates 10 DoF IMU modules (Filippeschi et al., 2017; Pala, 2018).

2.3.1.1. Accelerometer (Gyro)

UAV accelerometer measure static (gravitational) and dynamic (sudden acceleration or deceleration) accelerations along three axes. The sensor measurements uses gravitational acceleration g (9.8 m/s^2) or m/s^2 units (A. Zul Azfar and D. Hazry, 2011). Double integrating the output provides the position data, but drift may occur due to precision losses. The measurement range uses values of ±1g, ±2g, ±3g, ±4g, etc. Three-axis accelerometers detect gravity to determine downward direction which is crucial for rotary-wing UAV stability. The accelerometer typically resides on the flight control board (Altın, 2013; Çakıcı, 2019; Pala, 2018).

2.3.1.2. Gyroscope

A gyroscope measures angular velocity, representing movement around an axis. The measurement unit is expressed in degrees per second (°/s). It is used for direction estimation and adjustment. Like the accelerometer, a gyroscope cannot directly measure absolute angles and is subject to drift (Shaeffer, 2013).

2.3.1.3. Compass (Magnetometer)

An electronic magnetic compass measures the Earth's magnetic field along the x, y, and z axes to determine the UAV's orientation relative to magnetic north. The drift angle of the gyroscope is corrected using information from the compass (Asif et al., 2024).

2.3.1.4. Pressure gauge (Barometer/Altimeter)

The altimeter sensor functions as a digital barometer that measures altitude using pressure levels. Sea level serves as the reference point. As altitude increases from sea level, atmospheric pressure decreases. The pressure sensor monitors this change to determine UAV altitude. Altimeter sensors output altitude data in mmHg, or directly in meters or feet. Most flight control boards combine pressure sensor and GPS altitude data to achieve more accurate altitude measurements (Çetinkaya, 2017; Pala, 2018).

2.3.2. External sensors

This section explains sensors that are not featured on the control board. These sensors allow for the acquisition of desired data with high accuracy.

2.3.2.1. GPS

GPS remains the most precise and fastest method for location determination. The method uses location data from GPS satellites to determine point coordinates either statically or kinematically (Colombo and Evans, 1998). It now includes data from Glonass and Galileo satellites. This method provides coordinates in the international terrestrial reference frame (ITRF-96) coordinate system and has advanced to provide faster, more accurate coordinate determination through the CORS-TR method (Altınışık, 2019). **Figure 4** shows GPS positioning schematic.

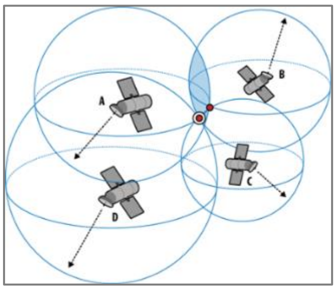

Figure 4. GPS positioning schematic.

Figure 5. A common GPS for UAVs.

There are 32 GPS satellites located 20200 km above Earth. These satellites regularly send time-stamped messages along with their position data to the Earth. GPS receivers use these messages to calculate their current position (Bretterbauer and Weber, 2003). GPS uses triangulation methods with satellites. While 27 satellites provide information, two-dimensional positioning required at least 3 satellites, and three-dimensional positioning needs at least 4 satellites. The intersection of these data points determines the current location which GPS sends to the device (Scott et al., 2016; URL, 2022d). Figure 5 illustrates a common GPS for UAVs.

2.3.2.2. Infrared sensor

Infrared sensors consist of two LEDs. One LED emits infrared light, while the other acts as a phototransistor, capturing the incoming light. The wavelength of the infrared beam can be adjusted. When the beam hits an object and reflects back onto the phototransistor, a signal is generated based on the intensity of the returning light (Kılıç, 2014). **Figure 6** shows the working principle of the infrared sensor.

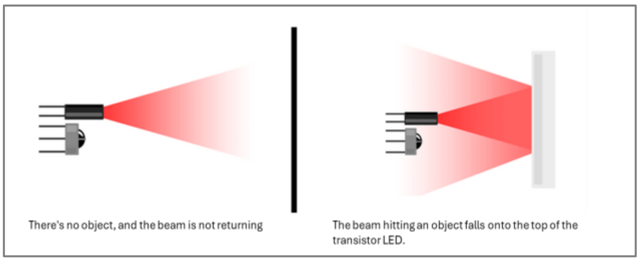

Figure 6. Working principle of the infrared sensor.

2.3.2.3. Anemometer

Anemometers are sensors that convert wind speed into electrical signals. There are three types of anemometers: cup, ultrasonic, and propeller.

a) **Cup anemometer:** Wind speed calculations use the time for the cup rotor to complete one rotation.
b) **Ultrasonic anemometer:** This design measures the time for sound waves to travel between transducers. The time difference determines wind speed.
c) **Propeller anemometer:** It operates similar to cup anemometers. When parallel to wind direction, it measures horizontal wind speed, and when perpendicular, it measures vertical wind speed.

Cup anemometers remain the most used type for wind speed measurements.

2.3.2.4. Voltage and current meter

The motor and control board are powered by a battery. To monitor this supplied energy, voltage and current meters are used.

2.4. Power distribution board

The power distribution board delivers energy to UAV components (T. Kidd et al., 2020). Motor operation requires power control units due to high currents (10 to 150 amperes) (Kaymak, 2019). Power modules vary based on system requirement. These modules regulate battery voltage, ensuring proper energy transfer to the control board for flight system operation (D. Erdos et al., 2013). An illustration of a common power distribution board for UAVs is presented in Figure 7.

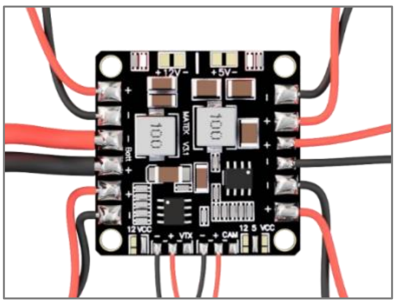

Figure 7. An illustration of a common power distribution board for UAVs

2.5. Motor

Motors provide thrust in quadrotors. While early quadrotors used gasoline, electric motors now dominate due to affordability and environmental benefits (Bin Junaid et al., 2018; Elmeseiry et al., 2021). UAV brushless DC motors use four-digit labels like AABB. AA represents stator width (diameter), and BB represents stator height (Balamurugan et al., 2020). In brushless motors, these measurements refer to copper winding dimensions inside the stator, unlike brushed motors, which use overall motor size. Larger width or height increases permanent magnet and electromagnetic coil sizes. Increased stator height emphasizes magnet size over coil size, while increased width prioritizes coil size. Extended stator size creates more surface area, intersecting more magnetic fields and improving cooling. These motors achieve higher power levels and speeds. Width increases add iron and copper, enhancing torque and efficiency (Elmas, 2019).

Motor bodies display codes like 12N14P**,** where N (poles) and P (magnets) indicate component counts. The number before N shows stator winding count, while the number before P shows permanent magnet count. Different motor sizes use varying pole and magnet numbers. Brushless DC motors, being three-phase, require pole numbers in multiples of 3 (9, 12, 15, 18) (Romano, 2018). Motors convert DC voltage to AC through three wires. Swapping output wires reverses rotation direction (Kaymak, 2019). UAV motor selection considers K_V rating, torque, weight, current draw, and connection mechanism.

2.5.1. Connection mechanism

Motor and propeller matching **is** crucial for design. UAV motors operate either inward or outward rotating. Inward rotating motors turn their internal rotor, while outward rotating motors turn their outer surface. Outward rotating motors offer easier propeller installation and system integration. Propellers attach to motors via plastic bands, connecting fittings, or shaft clamps. Secure attachment prevents flight vibrations (Batmaz, 2013).

a) **Brushed motor (inward rotating motor):** These convert electrical energy to mechanical energy by rotating windings inside fixed outer magnets. The rotor turns while stator windings remain stationary. Brushed refers to the armature-power cable connection. These motors show efficiency losses and shorter lifespans from brush and commutator wear (A. Junid et al., 2017). **Figure 8** shows an illustration of a brushless motor.

Figure 8. An illustration of a brushless motor.

b) **Brushless motor (outward rotating motor):** An ESC drives brushless motors (Eugene et al., 2019). The system creates a three-phase electromagnetic field between armature and power cables to generate rotation. Without brushes, these motors have less friction and quicker operation, achieving higher efficiency (typically over 80%). This efficiency increases cost for both motors and ESCs (A. Junid et al., 2017). **Figure 9** shows an illustration and components of a brushed motor.

Figure 9. An illustration and components of a brushed motor

Brushless motors provide longer operational life, higher efficiency, and eliminate additional gearboxes needed by brushed motors for high-speed torque. Their reduced friction enables up to 99% efficiency, extending flight time by approximately 50% compared to brushed motors (Öngül, 2017).

2.5.2. K_V rating

K_V defines the motor velocity constant in brushless DC motors, showing revolutions per minute (rpm) at 1 volt with no load. Simply put, K_V means revolutions per volt. Adding a propeller reduces RPM due to air resistance. Motors with higher K_V ratings attempt to spin the propeller faster and may draw more current. Higher K_V motors spin propellers faster but may draw more current. This requires larger propellers with lower K_V motors and smaller propellers with higher K_V motors. KV rating correlates with stator copper wire winding count. Magnetic strength of permanent magnets also affects KV rating; stronger magnets increase KV. Using high KV motors with oversized propellers forces operation as if with smaller propellers, demanding more torque, increasing current draw and risking overheating. Heavier UAVs typically use medium to low KV motors, while lighter UAVs use high KV motors (Elmas, 2019). For example, a 330 KV motor at 10 volts spins at 3300 RPM. With a 3S LiPo battery (12.6 V fully charged), the same motor reaches 4158 RPM without propeller (330 x 12.6).

2.5.3. Motor torque

Low K_V motors produce lower speeds but higher torque, while high K_V motors generate higher speeds and lower torque. High-torque motors respond more quickly due to their ability to change speeds rapidly, providing faster and more immediate reactions. In contrast, lower-torque motors exhibit slower, smoother responses (Elmas, 2019).

2.5.4. Weight

Another critical factor in motor selection is weight. The lightest motor is usually preferred in design. However, among motors with the same features, the lighter one often comes at a higher cost.

2.5.5. Current

Another important design parameter is the current drawn by the motor. Larger motors typically draw higher currents. Motors that draw high currents may operate less efficiently at lower speeds. In such cases, a smaller motor might enable the

UAV to take off more easily, while a larger motor might require more current to operate effectively (Batmaz, 2013).

2.6. ESC

ESCs control motor speeds (Green and McDonald, 2015). They primarily serve brushless motors, though brushed motors can operate without them using a flight control board power transistor (Özen, 2019). ESCs rank among the most crucial components and frequently appear in accident statistics. This necessitates high-quality, recommended products. Professional systems require high-amperage, quality ESCs (Kılıç, 2014). ESCs have specific characteristics and parameters that are essential for their selection. Generally, the following parameters are important when choosing an ESC (Öngül, 2017). ESCs can be used for both brushed and brushless motors. For brushless motors, ESCs are connected with three wires, while brushed motors are connected with two wires (URL, 2022a). An illustration of an ESC is given in Figure 10.

Figure 10. An illustration of ESC.

2.6.1. Voltage

The maximum voltage supported by ESCs indicates the maximum battery voltage they can handle. Exceeding this voltage may damage the ESC (Öngül, 2017).

2.6.2. Maximum burst current

An ESC handles maximum short-term current in bursts (about 10 seconds) but must not exceed its maximum rating. However, the maximum current should not be exceeded. Connecting motors that draw more current than this value could damage the ESC. The term burst varies and should be specified in parentheses. This value is not fixed due to various factors (Elmas, 2019; Öngül, 2017). ESCs are typically chosen based on the motor's expected peak current. An ESC with a rating about 1.2-1.5 times the motor’s maximum burst current is usually sufficient (Batmaz, 2013). For instance, a 2206 motor with a 5030 propeller draws 10 A at full thrust with a 4S LiPo battery, so a 12 An ESC would be adequate. However, if a 6045 propeller is used with the same motor, the maximum current draw might reach 20 A, in which case a 20 An ESC would be safer (Elmas, 2019).

2.6.3. Maximum continuous current

This is the maximum continuous current that ESC can support. ESCs can handle this current for extended periods. However, exceeding this value continuously may damage the controller. For UAVs and slow-flying aircraft, it is important to consider the maximum continuous current when selecting an ESC (Öngül, 2017).

2.6.4. Maximum rpm

This is the maximum rpm that an ESC can support. The rpm value specified might not directly correspond to the motor's rpm, as it is usually given along with the pole count. The maximum rpm is inversely proportional to the number of poles. For example, a controller rated for 240.000 rpm - 2 poles can operate a 4-pole motor at a maximum of 120.000 rpm (Öngül, 2017).

2.6.5. Pulse width modulation

Pulse width modulation (PWM) represents pulse width in square waves (Batmaz, 2013). It indicates the frequency range of the input signal that an ESC processes. Signals beyond this range remain unprocessed. This value is related to the signal from your radio device or flight controller (Öngül, 2017). ESCs connect to the control board and are managed via a PWM or digital signal (Özen, 2019). ESCs operate using PWM, with an update rate typically set at 50 Hz, which is sufficient for normal quadcopter operations. However, for applications requiring more agility and higher movement capabilities, ESCs with higher update rates should be used. Special or commercially available ESCs can operate at frequencies up to 450 Hz, or even 1 kHz with I2C protocol communication (Batmaz, 2013).

2.7. Battery and charger

The main limitation of a quadcopter is its flight time. Typically, a quadcopter's flight time is around 20 minutes. However, this time significantly decreases when carrying heavy payloads. With only the main components present, flight time can approach one hour (Carvalho, 2013). An illustration of a typical battery for UAVs is shown in Figure 11.

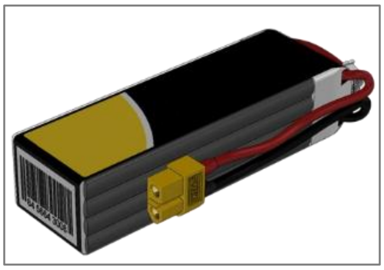

Figure 11. An illustration of a typical battery for UAVs.

Lithium Polymer (LiPo) batteries are recommended for multicopter systems (Kılıç, 2014). These batteries are commonly used in robots and are rechargeable (Çetinsoy et al., 2008). An illustration of a charger for battery of UAVs is presented in Figure 12. Here are some important considerations for battery use (Uz, 2019).

a) **Avoid constant charging:** Batteries should not be left on constant charge.
b) **Avoid extreme temperatures:** Batteries should not be exposed to excessive heat or cold.
c) **Battery type:** Use the type of battery suitable for the application.
d) **Charger:** Ensure that the charger is compatible with the battery used.
e) **Avoid short circuits:** Prevent short circuits in the battery.
f) **Do not fully discharge:** Batteries should never be left in a completely discharged state.

Figure 12. An illustration of a charger for battery of UAVs.

2.7.1. Battery technologies

Today, numerous battery technologies power UAVs (Altın, 2013; Uz, 2019). Each of these batteries has its own advantages in different areas. However, this section will discuss their pros and cons relevant to the study. The discussed batteries are as follows:

a) **Alkaline batteries:** These provide the most basic battery power. Using alkaline batteries means the quadcopter depends on non-rechargeable power. They work best where recharging proves impossible, such as in rural areas, forests, deserts, and other locations without power sources. These batteries are inexpensive and widely available. The main drawback concerns their low voltage and limited charge capacity. Most alkaline batteries are 1.5V with 700mAh capacity (Altın, 2013). For example, powering a motor needing 10.5V and 8A requires 7 batteries. Long-term alkaline batteries use proves impractical due to constant replacements, creating high costs and substantial waste.

b) **Nickel-Metal Hydride (Ni-MH) batteries:** These batteries dominate cordless phones. They represent the first rechargeable battery type, known for durability and reliability. They cost more than alkaline batteries and hold charge for shorter periods. Design challenges emerge because Ni-MH batteries max out at 9.5-10V. With DC motors, back electromotive force creates a 2-2.5V voltage drop, affecting ESC and motor power. Using two series-connected batteries adds weight. Ni-MH batteries stop working below certain capacity levels and need longer charging times versus other rechargeable types. They suit low-power systems where charging speed matters less, making them suboptimal for UAV projects (Altın, 2013; Uz, 2019).

c) **Nickel-Cadmium (Ni-Cad) batteries:** These feature low internal resistance, enabling high current output. They harm the environment. UAVs need high-energy-density power sources, but Ni-Cad batteries deliver low energy, requiring more units and increasing weight. They cost less and charge faster than Ni-MH batteries. Common in older laptops, they provide 1.2V nominal voltage. A 10.5V motor needs nine series-connected Ni-Cad batteries, each requiring individual charging. They share Ni-MH drawbacks for UAVs, offering only lower cost and faster charging benefits (Altın, 2013).

d) **Nickel-Zinc (Ni-Zn) batteries:** These power electric bicycles and vehicles but now serve smaller devices like cordless phones. They match Ni-MH and Ni-Cad sizes. Their 2.5-hour charging time makes them potential Ni-Cad alternatives (Altın, 2013).

e) **Lithium-Ion (Li-ion) batteries**: Li-ion batteries are among the most used battery types, along with LiPo batteries. They have high energy density but can be hazardous if not used properly. Li-ion batteries used in portable electronics are usually based on lithium cobalt oxide. Factors such as temperature, discharge current, charging current, and state of charge affect their lifespan. Li-ion batteries have low instantaneous high-current capabilities and can pose safety issues due to their high energy storage (Altın, 2013; Uz, 2019).

f) **Lithium-Polymer (LiPo) batteries:** Lithium-Polymer (LiPo) batteries represent the most advanced rechargeable battery currently available. They provide higher energy density per cell compared to predecessors though with slightly heavier. While conventional batteries deliver 1.2V to 1.5V per cell, LiPo batteries provide 3.6V to 4.7V per cell. LiPo batteries consist of series-connected individual cells, each with a nominal voltage of 3.7V. This enables higher-voltage power sources using fewer cells, reducing overall weight. The primary limitations of LiPo batteries involve cost and safety considerations. They exceed other types in price and permanent damage from rapid discharge. Each LiPo cell contains internal resistance (IR), limiting current draw according to Ohm's Law ($V = I \times R$ and $P = I^2 \times R$). Higher resistance increases power loss and heat generation, risking to overheating and damage during high-current operation (Altın, 2013; Elmas, 2019).

2.7.2. Cell count

The battery voltage is named according to the number of cells (S) in the battery (Elmas, 2019; Kaymak, 2019; Öngül, 2017). For example, a 14.8V battery is referred to as a 4-cell or 4S battery. The relationship between the number of cells and voltage is shown in Table 2.

Table 2. Relationship between number of cells and voltage

1S = 1 cell = 3.7V	2S = 2 cell = 7.4V	3S = 3 cell = 11.1V
4S = 4 cell = 14.8V	5S = 5 cell = 18.5V	6S = 6 cell = 22.2V

Voltage determines motor rpm. Higher cell count batteries increase UAV speed when motors and Electronic Speed Controller (ESC) support higher voltage (Elmas, 2019). After charging, each cell can provide up to 4.2V, but efforts should be made to avoid dropping below 3.4V during use, as this shortens the battery's lifespan. If the cell voltage falls below 3V, the cell is likely to quickly become unusable (Batmaz, 2013).

A LiPo battery combines one or more cells, each providing 3.7V nominal voltage. Series and parallel connections modify battery voltage and current capacity (Pala, 2018). **Figure 13** shows the schematic of batteries with a configuration of 4 series and 2 parallel (4S2P) connections (Pala, 2018).

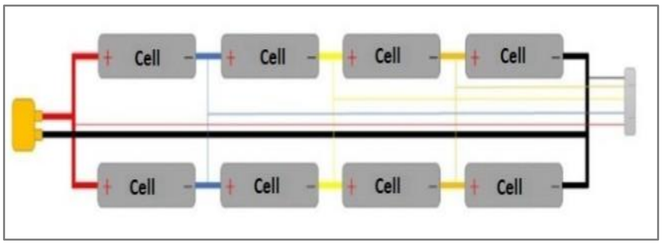

Figure 13. Schematic of a 4S2P battery with parallel and series connections

2.7.3. Capacity

Battery capacity uses mAh (milliampere-hours) measurements**.** mAh shows one-hour current draw before depletion (Elmas, 2019). For example, a 1300 mAh LiPo battery will be fully depleted in one hour if a constant current of 1.3A is drawn. If the current drawn is 2.6A, the time will be halved (1.3 / 2.6 = 0.5).

2.7.4. Discharge rate

The discharge rate (C rating) represents continuous discharge in LiPo batteries. Manufacturers print this rating on battery fronts. The C rating determines safe maximum constant current draw (Elmas, 2019):Maximum Current = Capacity x Discharge C Rating For example, a 3S 1000mAh 20C discharge rate LiPo battery can safely provide a maximum current of 1000mAh x 20C = 20A.

2.7.5. Charge rate

The charge rate is the inverse of the discharge rate, indicating the maximum constant current that can be safely applied during battery charging. The standard rate is typically 1C. The formula for calculating the charge rate is: Maximum Charging Current = Capacity x Charge C Rating. For example, a 3S 1000mAh LiPo battery with a 1C charge rate can safely accept a maximum charging current of 1000mAh x 1C = 1A

Goli et al. (Goli et al., 2023) conducted a comprehensive analysis of various motor-propeller-battery configurations, examining three motor types, five propeller designs, and two battery capacities. Their testing revealed that the 6000 mAh battery (B2) demonstrated superior performance characteristics compared to the 3300 mAh battery (B1), achieving higher motor speeds with lower current consumption to generate equivalent thrust. The study identified optimal component combinations, with the 12-inch diameter propeller (P4) achieving efficiency ratings of 12.9% with B1 and 11.4% with B2. The 700 KV motor (M1) proved most efficient, reaching 64.29% efficiency when paired with B1 and 62.01% with B2. Notably, the B2 configuration significantly enhanced payload capacity, supporting 5.82 N compared to B1's 2.02 N. Flight endurance tests, both with and without payload, consistently showed better performance with the B2 battery configuration.

2.8. External hardware

2.8.1. Arduino microcontroller

Arduino is an open-source microcontroller board produced by an Italian company, featuring a programmable microprocessor. Its simplicity, ease of programming, and Input/Output pins make it suitable for small to medium-sized projects (Bulut, 2019). An Arduino microcontroller can be programmed to read various data from UAV. For example, it can monitor the rpm data during flight through sensors or save collected data to an external SD card via an SD card module. Figure 14 depicts an illustration of Arduino microcontroller.

Specialized UAV hardware configurations can be effectively deployed for precision agriculture applications, particularly in weed detection and management. A notable example is demonstrated in Nagothu et al. (Kumar Nagothu et al., 2023)'s research, where they integrated a microcontroller and camera system for automated weed identification in agricultural fields. Their implementation leveraged machine learning algorithms to precisely locate weed infestations that could potentially impact crop yields. The system demonstrated impressive performance, achieving 91% accuracy in testing conditions and 94% accuracy with training data, highlighting the effectiveness of UAV-based solutions in agricultural monitoring and management.

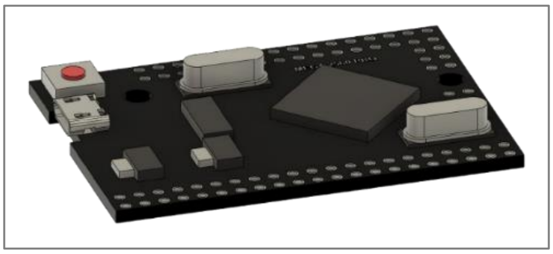

Figure 14. An illustration of Arduino microcontroller.

2.8.2. Secure digital card module and external memory card

A secure digital (SD) memory card is a data storage device. It was first introduced by SanDisk in 2001, based on the development of multimedia card technology. The SD card module can store operation results in text file format. This module records real-time data from other components (Bulut, 2019). An illustration of SD card module is given in Figure 15.

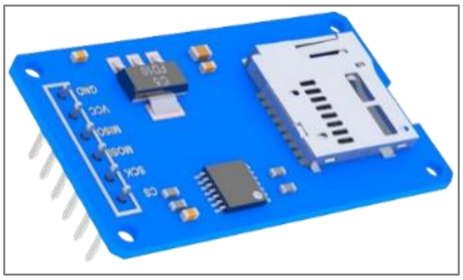

Figure 15. An illustration of an SD card module.

2.9. Motion control

There are two methods for controlling UAVs. It can be controlled directly with a remote control or through various software like ground control stations via devices such as computers, tablets, or smartphones. The choice between these methods depends on user requirements. The fundamental difference between the two systems is autonomous operation capability. In autonomous operation, the system operates independently without pilot intervention. The UAV executes pre-planned routes by itself (Raimundo, 2016; URL, 2022b).

2.9.1. Remote control and transmitter/receiver

The pilot commands the UAV using a control system that has existed for approximately 60 years. RC systems manage UAVs and transmit data including direction, motor speed, and servo controls. RC communication requires a transmitter and receiver. UAVs use four basic channels: roll, pitch, yaw, and throttle. Additional channels enable functions like arming/disarming the motors, changing flight modes, controlling camera equipment (gimbal), and releasing payloads (Pala, 2018). While remote control technology has evolved from single channel to multi-channel, and from AM, FM, and PPM to 2.4 GHz, the basic principles remain unchanged (Kılıç, 2014). Figure 16 shows an illustration of a remote-control device. Commands are transmitted from the radio transmitter on the controller to the receiver (Pala, 2018).

Figure 16. An illustration of a remote-control device.

Communication between the controller and the receiver uses various protocols. The receiver forwards signals to the controller, which then manages the UAV based on the RC signals. Telemetry-equipped controllers can be used. For example, critical information like the UAV's battery status can be transmitted to the controller in real time (Pala, 2018). An illustration of a remote-control transmitter is presented in Figure 17.

Figure 17. An illustration of a remote-control transmitter.

2.10. Propeller

A propeller is a critical component in aerial vehicles, converting rotational motion into propulsive force (Çelebi et al., 2024; H. N. P. Wisudawan et al., 2024). Effective propeller design requires a balance of durability, lightweight construction, rigidity, and consistent performance across various operating conditions. Propellers come in two rotational configurations: clockwise (CW) and counterclockwise (CCW). Their specifications are typically expressed in a diameter x pitch format, where pitch represents the theoretical distance the propeller would travel in a single complete rotation (M. B. Swedan et al., 2023).

Gajula and Tara (Gajula and Tara, 2023) conducted a study on optimizing motor-propeller combinations for a 500mm quadcopter frame. They evaluated three propeller variants (carbon fiber 8045, nylon 9045, and nylon 1045) paired with two motor options (2213 935KV and Generic 2212-1000 KV). Through systematic testing and precise calibration, they achieved remarkable improvements in performance. The optimized configuration, utilizing a Nylon 1045 propeller with a Generic 2213-935 KV motor, demonstrated a 43% increase in flight time compared to their initial efficient setup. This optimization extended the flight duration from 16 minutes to 23 minutes, highlighting the critical importance of component selection and proper system calibration in UAV performance.

3. Software

The software used on UAVs and ground stations varies. This software can be categorized into two groups: the software used on the flight control board of the UAV and the software used on the ground station.

3.1. Flight control board software

Flight control board software typically focuses on specific hardware, technology, or purposes. Some of the software used in flight control boards include Ardupilot, Baseflight, MultiWii, Cleanflight, Betaflight, iNav, OpenAero, and KISS (Pala, 2018).

3.1.1. Ardupilot

Ardupilot is the leading flight control board software for rotary-wing aircraft. The software controls multiple vehicle types, including fixed-wing and rotary-wing aircraft, hybrid vehicles, ground vehicles, and boats. Ardupilot software comprises three sections: Ardupilot for fixed-wing aircraft, Arducopter for rotary-wing vehicles, and Ardurover for ground-based vehicles (Peksa and Mamchur, 2024).

3.1.2. Baseflight

Baseflight was one of the first widely used 32-bit flight control board software, based on the 8-bit MultiWii flight controller software. However, Baseflight is no longer being updated today (Pala, 2018).

3.1.3. Multi Wii Copter

Multi Wii Copter is an autonomous system specifically developed for rotary-wing UAVs. It is open source, with all developments carried out by users, allowing observation of the program's evolution over time. The open-source nature of the system provides high software flexibility. However, Multi Wii Copter lacks consistency in advanced functionalities (Kumar et al., 2015).

3.1.4. Cleanflight

Cleanflight emerged an improved and user-friendly version of Baseflight aiming for wide use and reliability. Over time, Cleanflight evolved into Betaflight and iNav, which incorporated many new features, and was later merged as Cleanflight 2.0. However, there has been a significant slowdown in its development and updates (Pütsep and Rassõlkin, 2021).

3.1.5. Betaflight

Betaflight supports many flight control boards. It serves rotary-wing vehicles and fixed-wing FPV (First Person View) aircraft. The software benefits racers, acro/freestyle pilots, and beginners, remaining open source. The developers of Betaflight focus on reading sensor data at 32 kHz and sending this data to the motor to operate the flight controller and vehicle at the highest speed and performance (Pütsep and Rassõlkin, 2021).

3.1.6. iNav

iNav emphasizes navigation and autonomous vehicle features, including waypoint missions, return-to-home (RTH), and even autonomous landing. This open-source software incorporates features from Cleanflight with regular updates. It supports multi-rotor rotary-wing and fixed-wing vehicles (Pütsep and Rassõlkin, 2021).

3.1.7. Pixhawk

Pixhawk represents an open-source autopilot system for affordable autonomous aircraft. Pixhawk uses the same telemetry protocol (MAVLink) as Ardupilot, making it compatible with ground station software like QGroundControl. Both software systems are similar in terms of autonomous flight capabilities. The main difference lies in their commercial licensing: modifications to Pixhawk do not need to be disclosed as open-source, whereas developments made with Ardupilot for commercial use must be shared as open-source code (Peksa and Mamchur, 2024).

3.1.8. Keep It Super Simple

Keep It Super Simple (KISS) comes from Flyduino, which has been making rotary-wing vehicle components since 2011. It is closed-source and developed more slowly compared to open-source software. KISS is one of the most suitable flight control board software options for racing and acrobatic flight (Pala, 2018).

3.2. Ground control station systems

A ground control station serves as the central command interface software that enables operators to manage various aspects of UAV operations. It provides comprehensive functionality for mission planning and execution, real-time telemetry data monitoring, and direct flight control command issuance. Through this interface, operators can effectively oversee and manage autonomous UAV operations while maintaining continuous monitoring of flight parameters and system status (Aliane, 2024). UAVs operate using various remote control methods such as computers, tablets, autonomous software, or smartphones, and can operate under complete artificial intelligence (AI) control (Özen, 2019). The autopilot, or auto pilot, refers to a series of control mechanisms designed to keep an aircraft continuously stable in a horizontal position at predetermined coordinates and to issue commands to return to its previous position in case of changes. Ground station software manages tasks such as mission loading, mission execution, obtaining vehicle location information, and reviewing flight records (Pala, 2018). The term autopilot is derived from automatic pilot. Today, it means that all operations typically performed by a pilot are handled by an automated device. Autopilots function in air, land, sea, and space vehicles (Batmaz, 2013).

An autopilot system is a feature of the control board. When selecting a control board, it is important to consider whether the board includes autopilot software or if it can be added through later software updates. During route missions, maintaining stability can be challenging due to various internal (software or hardware) and external (weather conditions) factors. This difficulty is exacerbated with manual control. Automated flight and processor-managed control enhance the stability and performance characteristics of the quadcopter.

3.2.1. QGroundControl

QGroundControl enables autonomous flight control and mission planning for UAVs. As open-source software, it allows users to contribute to or customize its features for specific UAVs. QGroundControl supports all vehicle types (rotary-wing, fixed-wing, VTOL, etc.) compatible with ArduPilot and Pixhawk Pro. It functions across all platforms and mobile devices (T. Dardoize et al., 2019).

3.2.2. Mission Planner

Mission Planner is a fully featured ground station application. Through Mission Planner, flight data monitoring, mission planning, and flight simulation are possible. Multiple target points at various altitudes can be defined. Flight log files can be downloaded and reviewed (Peksa and Mamchur, 2024).

Suparta et al. (Suparta et al., 2023) developed an automated delivery system using a quadcopter equipped with MissionPlanner autopilot software. Their hardware configuration consisted of an APM 2.8 flight controller, Ublox NEO M8N GPS module with compass, Racerstar 920kV 2-4S Brushless Motors, Flysky FS-iA6B receiver paired with FS-i6 transmitter, DJI F450 frame with landing skids, and a 3300 mAh 35C LiPo battery. The payload system incorporated a BME280 sensor array controlled by an Arduino Uno R3 SMD. Navigation was implemented through waypoint programming using Mission Planner's Google Maps interface, with the BME280 barometer providing altitude verification at each waypoint. Testing demonstrated a 5% average positional error at waypoints, validating the viability of system for precise cargo delivery applications.

3.2.3. APM Planner 2.0

APM Planner 2.0 combines the user-friendly interface of Mission Planner with the multi-platform capabilities of QGroundControl software (Pala, 2018).

3.2.4. EZ-GUI

EZ-GUI is ground station software compatible with iNav, Cleanflight, Betaflight, and MultiWii-based flight controllers. It transmits flight control board data to the ground station. The software can perform mission loading. Its Android compatibility enables mobile devices to function as ground stations in the field (Pala, 2018).

4. Communication System

The first step in establishing a communication system is deciding the conditions for UAV communications. Depending on the design, UAVs can send data to the user during or after flights. Similarly, a UAV may complete the flight without intervention after pre-flight task uploads, or the user can send commands to the UAV during flight (Batmaz, 2013).

Telemetry, by definition, refers to the remote monitoring or control of a system or facility, either wired or wireless. In UAV systems, telemetry transmits data such as battery status, altitude, speed, and position. In complex UAV systems where long-distance image and data transmission is required, high-gain and powerful receiver systems and directional antennas are needed. The size of these systems may increase due to the need for encrypted data transmission (Kılıç, 2014). The most significant advantage of an unmanned aerial vehicle is its remote controllability. During remote control, signals are sent to the receiver according to the user's requests via a transmitter, and these signals are interpreted through a microprocessor to control the UAV. Telemetry technologies include radio frequency remote control, Bluetooth control, computer control via wireless connection (WIFI), and infrared control systems. Before using these technologies, factors such as cost, application difficulty, and communication with microprocessors should be considered (Altın, 2013; Hoang and Poon, 2013) A general comparison of telemetry technologies for remote control is provided in Table 3 (Altın, 2013).

Table 3. Comparison of telemetry technologies.

Type	Radio Frequency	Wi-Fi	Bluetooth	Infrared
Operating Voltage	9-12V DC	9-12V DC	9-12V DC	6-9V DC
Communication Range	MHz	GHz	GHz	kHz
Average Price	Low	High	High	Low
Usage Difficulty	Medium	Medium	Medium	Low

4.1. Radio frequency

Radio frequency (RF) control uses radio waves at specific frequencies sent to a radio frequency receiver. The receiver uses a decoder to ensure that transmitted frequency signals are not interfered with or stopped by other frequencies emitted by hundreds of devices in the location. RF motion control technology has both advantages and disadvantages. Among the advantages: Unlike other motion control technologies, RF technology does not require the receiver to have a direct line of sight to the transmitter; hence, obstacles like walls do not negatively affect the signals sent to the receiver. RF technologies offer long ranges of communication, allowing for control from considerable distances. Since radio frequencies are not affected by light or weather conditions, they are ideal for outdoor environments. However, RF technology also has its disadvantages. Other devices operating on the same frequencies can interfere with the RF signals. Another drawback is security; transmitted signals can be detected by other receivers. The higher cost of RF technology can be a disadvantage for budget-constrained projects. Additionally, the slower speed of communication between the receiver and transmitter compared to other technologies can be a drawback. Despite these disadvantages and the higher cost, RF technology remains indispensable for projects requiring remote control (Altın, 2013).

Telemetry is an essential communication device for autonomous vehicles. This communication is achieved with one module on the vehicle and another on the ground. The ground pilot draws the necessary flight path for autonomous flight, and the ground telemetry module communicates with the vehicle telemetry module, sending this information to the control board (Özen, 2019). Radio-based telemetry, as shown in Figure 18, is used for data transfer between the unmanned aerial vehicle and the ground station, allowing for remote monitoring of the vehicle (Pala, 2018).

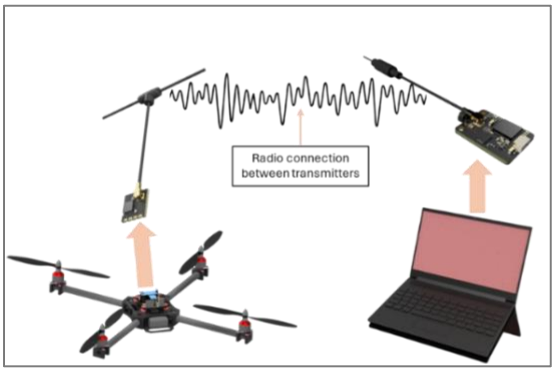

Figure 18. Telemetry system.

Varun et al. (M. Varun et al., 2023) conducted research on telemetry implementation in quadcopter systems, demonstrating how telemetry capabilities enable real-time remote monitoring and system control. Their findings highlighted the significant value of telemetry data in analyzing UAV performance metrics and operational behavior, providing operators with crucial insights for effective drone management and mission execution.

4.2. WIFI

This technology, commonly known as WIFI, derives its name from the initials of Wireless Fidelity (URL, 2022c). It enables communication at higher frequencies. WIFI allows different computers or devices to communicate wirelessly over a shared network. WIFI uses radio waves, operating at 2.4GHz, 3.6GHz, or 5GHz. WIFI adapters convert digital code into radio signals for communication and then interpret incoming radio signals back into digital codes. The advantages of WIFI communication include the lack of need for cables, as communication is done wirelessly. WIFI supports connections with multiple devices and allows for multi-point control. Additionally, Wi-Fi includes security measures such as firewalls to block external interference or unauthorized access, providing a secure control process. However, WIFI also has disadvantages. As the distance from the transmitter increases, the speed and accuracy of the connection can be significantly affected. WIFI technology is also quite expensive. Devices operating with WIFI consume more power compared to those using other communication technologies, leading to larger power consumption and battery size, and shorter active operation time (Altın, 2013).

4.3. Bluetooth

Bluetooth technology, like WIFI and radio frequency technologies, uses radio waves for communication between the transmitter and receiver. Due to its widespread use, Bluetooth provides an alternative method for controlling UAVs. The advantages of Bluetooth include flexibility in controlling the UAV using devices like computers, PDAs, and mobile phones, as Bluetooth is commonly found in these devices. Bluetooth is also easy to use, and its low power consumption benefits battery life. The range of Bluetooth devices depends on the power used; at 100mW, the range is 100 meters; at 2.5mW, 22 meters; and at 1mW, it is 6 meters, with 1mW modules being the most common. The maximum range is typically limited to 50 meters. However, Bluetooth has some disadvantages, such as lower data transfer capacity and potential security issues. A Bluetooth device may automatically attempt to connect to other Bluetooth devices, which can be a security concern (Altın, 2013; ArduPilot, 2020).

4.4. Infrared

Infrared technology uses light emitted by an LED to send signals to receiver devices for motion control. Typically, infrared motion control transmitters operate between 32 and 40 KHz. The transmitter communicates with the receiver by sending pulses in binary code via infrared light, which are then decoded by a microprocessor to fulfill the user's commands. The advantages of infrared technology include low power consumption, making it suitable for controlling many devices during the day. It is also inexpensive, integrates easily with other devices or microprocessors, and is generally compact and less affected by signals from other devices. However, infrared technology has limitations. Like television remote controls, infrared transmitters and receivers must have a direct line of sight. Any object, such as a person or wall, blocking the path between the transmitter and receiver can interrupt communication. The range of infrared technology is shorter compared to other technologies, and communication performance decreases with increased distance between the transmitter and receiver. Additionally, environmental factors like sunlight, rain, smoke, and fog can degrade transmission quality between the transmitter and receiver (Altın, 2013).

4.5. Flight control software

To enable a UAV to perform autonomous flight missions, it must be equipped with four fundamental electronic components: an autonomous flight-supporting flight control board, a GPS transmitter and receiver, an IMU for converting

GPS data, and telemetry devices for transmitting this data to other targets. These components are essential for autonomous vehicles, with GPS being mandatory. The hardware and features fully support the selected equipment. During route navigation, maintaining stability can be challenging due to various internal (software or hardware) and external (weather conditions) factors. This challenge is particularly pronounced during manual control. Pre-defined automatic or autonomous flight, where all control is managed by the processor, enhances the stability and performance of the quadcopter.

5. AI based applications

AI has emerged as a transformative technology that imbues machines with intelligence, enabling them to perform tasks with capabilities that can surpass human performance. The integration of AI within UAV networks presents both challenges and opportunities in modern applications (Aliane, 2024). AI methodologies in UAV applications can be categorized into two distinct levels of intelligence. The first level encompasses fundamental methods that enable predictable environmental responses, allowing UAVs to operate according to specific performance metrics. The second level comprises more sophisticated methods that enable UAVs to interact with their environment and make autonomous decisions in unpredictable conditions (S. Rezwan and W. Choi, 2022). This integration of AI into UAVs enhances their communication capabilities, networking efficiency, and flight safety, ultimately improving their service quality in IoT applications (N. Cheng et al., 2023). While AI-based UAV network design is an ongoing research area, AI-based UAV technology focuses on various areas, including:

a) **Security and privacy issues:** Security concerns in UAV systems require a comprehensive approach across multiple levels including hardware, software, communication, and sensor systems (Mekdad et al., 2023). Modern AI-based solutions are being developed to address various security threats, particularly focusing on cyber-physical attack prevention (Sarkar and Gul, 2023).

b) **UAV network design issues:** Despite the advantages of drone technology, significant challenges persist in network implementation. The primary constraints stem from limited payload capacity, affecting power consumption, communication range, and computational capabilities. UAV networks face unique challenges due to their dynamic nature, characterized by high-speed movement and varied maneuverability in obstacle-sparse environments. Traditional ground-based protocols prove inadequate for UAV applications, necessitating AI-based networking and control solutions that leverage advanced deep learning methods and modern computational platforms (Rovira-Sugranes et al., 2022).

c) **Localization and trajectory:** AI-based approaches are crucial for optimizing location and path determination, particularly in addressing the demands of real-time calculations required in dynamic UAV operations (Afifi, 2023).

d) General applications: The application scope of UAV networks continues to expand, encompassing integration with cellular networks, vehicular systems, coverage of high-risk areas, and spectrum utilization optimization (Sarkar and Gul, 2023).

6. Conclusions and Future Directions

This comprehensive review of multirotor UAV systems, with a focus on quadcopters, highlights the rapid advancements and increasing complexity in this field. The paper covers key components and technologies essential for UAV design and operation, including frame types and materials, flight control boards, motors, electronic speed controllers, batteries, propellers, and communication systems. The evolution of UAV technology has led to applications across various sectors, from military and agricultural uses to disaster management and urban planning. The integration of sophisticated sensors, GPS systems, and advanced flight control software has enhanced these systems, allowing for autonomous flight, precise navigation, and complex mission execution. Current challenges in UAV integration include battery technology limitations affecting flight duration, restricted communication ranges, weather-related operational constraints, complex regulatory and certification requirements, and ongoing security and privacy concerns. These factors continue to present significant hurdles for widespread UAV adoption in everyday applications. However, as UAV technology advances, new solutions and opportunities are emerging to address these challenges. As UAV technology continues to evolve, several key areas emerge as focal points for future research and development:

- Energy efficiency technologies such as energy beam-forming and distributed multipoint wireless power transfer.
- Integrating advanced battery applications such as hydrogen fuel cells, improved lithium-ion batteries and solar energy.
- Enhanced autonomous capabilities using onboard computer-vision-based systems.
- Integrating AI and machine learning in terms of battery optimization, route planning, obstacle detection, monitoring, and resource allocation (e.g., computing and battery).
- Using higher communication networks such as 5G and even 6G.
- Improved safety features and fail-safe mechanisms using blockchain and physical layer security.
- Advanced materials for lighter and more durable frames such as glass fiber reinforced polymer, carbon fiber reinforced polymer and Kevlar fiber reinforced polymer.
- More sophisticated sensor technologies integration such as thermal infrared sensors, small unmanned aircraft system-mounted light detection and ranging (sUAS-borne LiDAR), and hyperspectral sensors.
- Development of standardized regulations for UAV operation in various contexts.

The field of UAV technology continues expanding, with new applications and innovations emerging regularly. As these systems become more sophisticated and widely adopted, they will play an increasingly important role in various industries and aspects of modern life. Future research and development in this area will address current limitations and unlock the full potential of UAV technology.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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