WIDE-BODY AIRCRAFT SELECTION USING MULTI-CRITERIA DECISION MAKING METHODS

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ABSTRACT

WIDE-BODY AIRCRAFT SELECTION USING MULTI-CRITERIA DECISION MAKING METHODS

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Aircraft acquisition is a major investment that can be defined as a strategic activity as it effects the long-term plans of an airline. The selection of an aircraft requires a detailed assessment process since it involves various criteria and alternatives. Thus, aircraft selection can be identified as a multi-criteria decision making (MCDM) problem, which is investigated in this study using a combination of three different MCDM methods, namely Analytic Hierarchy Process (AHP), Decision Making Trial and Evaluation Laboratory (DEMATEL) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This study uses a comprehensive set of criteria that is associated with aircraft selection, and utilizes AHP and DEMATEL methods to obtain two sets of criteria weights based on expert judgments, which are then combined with TOPSIS method to determine the best wide-body passenger aircraft for airlines. Moreover, the interactions between aircraft selection criteria are investigated and presented with impact relation maps through the use of DEMATEL method. The use of AHP-TOPSIS and DEMATEL-TOPSIS approaches enable to examine the effects of the assumption of criteria independency in the aircraft selection context. The results of the study show that the ranking of alternatives change across the approaches, which is attributed to the effect of criteria independency assumption in AHP method when determining criteria weights.

Keywords: Aircraft selection, Multi-Criteria Decision Making (MCDM), Analytic Hierarchy Process (AHP), Decision Making Trial and Evaluation Laboratory (DEMATEL), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

ÖZ

ÇOK KRİTERLİ KARAR VERME YÖNTEMLERİ İLE GENİŞ GÖVDELİ YOLCU UÇAĞI SEÇİMİ

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Uçak alımı hava yollarının uzun vadeli planları üzerinde etki sahibi olan büyük bir yatırımdır. Alınacak uçağın seçimi çeşitli kriter ve alternatiflerin dahil olduğu detaylı bir değerlendirme gerektirmektedir. Bu nedenle, uçak seçimi çok kriterli karar verme (ÇKKV) problemi olarak tanımlanabilir. Bu çalışmada bu problem Analitik Hiyerarşi Süreci (AHS), DEMATEL (Decision Making Trial and Evaluation Laboratory) ve TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) adlı ÇKKV yöntemlerinin kullanımı ile incelenmiştir. Bu çalışmada uçak seçimi ile ilgili kapsamlı bir kriter seti kullanılmış ve kriter ağırlıkları uzman görüşleri kullanılarak AHS ve DEMATEL yöntemleriyle belirlenmiştir. Elde edilen kriter ağırlıkları daha sonra TOPSIS yönteminde hava yolları için en iyi geniş gövdeli yolcu uçağının belirlenebilmesi için kullanılmıştır. Ayrıca, uçak seçim kriterleri arası etkileşimler DEMATEL yöntemi kullanılarak incelenmiş ve etki ilişki haritaları ile gösterilmiştir. AHS-TOPSIS ve DEMATEL-TOPSIS yaklaşımlarının kullanımı uçak seçim probleminde kriter bağımsızlığı varsayımının etkilerini araştırma imkânı sağlamıştır. Çalışmanın sonucunda, kullanılan iki yaklaşımın farklı sıralamalar ortaya çıkardığı görülmüştür. Alternatiflerin sıralamalarındaki farklılık, AHS yönteminde kriterlerin bağımsız olduğu varsayımının yapılmasına dayandırılmıştır.

Anahtar Kelimeler: Uçak seçimi, Çok Kriterli Karar Verme (ÇKKV), Analitik Hiyerarşi Süreci (AHS), DEMATEL, TOPSIS

To Başak and My Family

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LIST OF ABBREVIATIONS

AEA	Association of European Airlines
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CI	Consistency Index
CR	Consistency Ratio
DEMATEL	Decision Making Trial and Evaluation Laboratory
DM	Decision Maker
DOC	Direct Operating Cost
DRM	Direct Relation Matrix
EASA	European Union Aviation Safety Agency
EPNdB	Effective Perceived Noise in Decibels
ETOPS	Extended Range Twin-engine Operations Performance Standards
FAA	Federal Aviation Administration
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IRM	Impact Relation Map
MCDM	Multi-Criteria Decision Making
MTOW	Maximum Take-off Weight
NM	Nautical Mile
PCM	Pairwise Comparison Matrix
RI	Random Consistency Index
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRM	Total Relation Matrix
ULD	Unit Load Devices

CHAPTER 1

INTRODUCTION

Air transportation has been a continuously developing transportation mode in terms of passenger growth. According to International Civil Aviation Organization (ICAO, n.d.-b), the airline industry has seen a compound annual growth rate of 5.4% in revenue passenger kilometers between 1995 and 2015. Despite having had a major setback in the number of flights globally due to the COVID-19 pandemic, the International Air Transport Association (IATA, 2021c) predict a return to pre-pandemic traffic levels by 2023, and Airbus (2021d) and Boeing (2021a) forecast an average traffic growth rate of about 3.9-4.0% in the next 20 years. Boeing also forecasts that a total of 43,610 new aircraft will be required and 7,670 of these will be wide-body passenger aircraft. To meet the increasing demand and replace existing fleets, airlines need new aircraft, and require successful fleet planning practices.

From an airline perspective, fleet planning is a business process in which companies acquire aircraft to provide capacity for both existing and future destinations (Clark, 2007). It is a strategic planning activity as buying aircraft are major investments for airline companies, and since the capabilities of these aircraft play a vital role in the profitability of airlines. Although selecting a type of aircraft requires the assessment of a wide variety of criteria, Belobaba et al. (2016) state that airlines generally approach this decision problem as a financial one, and argue that other aircraft characteristics must be factored in as well. As this is a complex process that involves various criteria and alternatives, the selection of an aircraft can be identified as a multi-criteria decision making (MCDM) problem that has attracted the attention of researchers.

In the literature, there are a number of studies that have investigated the case of aircraft selection for airlines using MCDM methods. However, there are certain improvement areas in this specific problem, particularly with the criteria involved in this problem, such as the inclusion of certain criteria and the issue of interactivity among criteria. In this study, a comprehensive set of criteria related to the selection of a wide-body passenger aircraft is used. It proposes the use of two different MCDM methods, Analytic Hierarchy Process (AHP) and Decision Making Trial and Evaluation Laboratory (DEMATEL), to determine two sets of criteria weights to be used in conjunction with another method, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Using the AHP-TOPSIS and DEMATEL-TOPSIS approaches, the wide-body passenger aircraft selection problem is solved and the effects of the assumption of criteria independency are investigated. Interdependency of criteria issue is addressed with the usage of DEMATEL method, and influences between criteria are determined and displayed with impact relation maps (IRMs) of criteria. By providing a solution to this complex problem, this study aims to provide decision support for airlines and decision makers (DMs) in their fleet planning processes.

The rest of the study is structured in the following way: Chapter 2 presents a review of the relevant literature on the selection of an aircraft. Chapter 3 provides the application procedures of AHP, DEMATEL and TOPSIS methods, and the discussion on the combination of these methods which form the two approaches to be undertaken. The chapter continues with the definitions of the criteria and brief descriptions of the alternative aircraft. In Chapter 4, the results of the study are given. Lastly in Chapter 5, final remarks, limitations and future research directions are provided.

CHAPTER 2

LITERATURE REVIEW

In this chapter, relevant research in the area of multi-criteria aircraft selection problem is presented. Then, aircraft selection criteria and the consideration of criteria dependency sections follow. Also, a section on the application areas of AHP, DEMATEL and TOPSIS methods is presented. The discussed studies involve the selection of regional aircraft, narrow-body, and wide-body aircraft for airline companies.

It should be mentioned here that, the term aircraft selection is used in the literature not only for passenger aircraft, but also for the selection of training aircraft, military fighter jets, freighter aircraft, single-engine aircraft, and unmanned aerial vehicles. However, as the constituents involved in these studies, such as DM(s), criteria, and alternatives differ from that of a passenger aircraft selection setting, these studies are not included in this literature review.

2.1. Passenger Aircraft Selection Studies

In a study by See et al. (2004), a hypothetical and simplistic aircraft selection case is examined to show the applicability of a multi-attribute decision making method named hypothetical equivalents and inequivalents, in single DM setting. The authors include three attributes and four alternatives in their study. See et al. (2004) state that MCDM methods that obtain criteria weights through assessments of DMs have drawbacks since these assessments are based on experience and intuition. However, the authors utilize the preferences of DMs to derive weights for criteria, which are also based on experience of DMs.

Yeh and Chang (2009) use fuzzy group MCDM to evaluate five different aircraft for a domestic Taiwanese airline. They categorize eleven sub-criteria under three main criteria, and use pairwise comparisons to obtain the weights of both qualitative and quantitative criteria. Later, to acquire the performance values of alternatives, the authors utilize triangular fuzzy numbers to handle the inaccuracies of subjective judgments made by individual DMs. They aggregate the individual judgments with the geometric mean method. The authors propose a modified TOPSIS method to rank the alternatives, in which they use criteria weights to obtain weighted distances from the positive and negative ideal solutions, rather than using a weighted normalized decision matrix.

Sun et al. (2011) use various MCDM methods for a hypothetical aircraft selection case. Along with five different criteria, robustness criterion is proposed to reflect uncertainties in this context resulting from the volatility of fuel prices and demand. Taguchi loss functions are used to check robustness. The authors utilize AHP for the determination of criteria weights and compare the results obtained from Elimination and Choice Expressing Reality (ELECTRE), Simple Additive Weighting (SAW) and TOPSIS methods. Also, sensitivity analysis is carried out to detect the effects of criteria on rankings.

For an aircraft selection study for Turkish Airlines, Özdemir et al. (2011) use the Analytic Network Process (ANP) method to select the best alternative among three mid-ranged, narrow-body aircraft. In their study, ten criteria and three alternatives are identified based on expert opinion. The criteria involved in the study are related to aircraft costs, physical attributes, and time. The study reveals Boeing 737 as the best among the alternatives.

Gomes et al. (2012) carry out a case study for a regional charter airline startup in Brazil. The managers of the company are involved in modelling the problem, where they decide on criteria to be used in the study through literature research, and on alternative selection with a limitation on the number of maximum passengers, which ensures a reduction on operating costs. The criteria involved are of stochastic, fuzzy, and numeric type. The authors divide the criteria into main and sub-criteria, where main criteria are defined as financial, logistics, and quality. In the study, criteria applicable for a regional aircraft are chosen, such as flexibility, replacement parts availability, landing and take-off distance, and avionics availability. To solve the problem, they use Novel Approach to Imprecise Assessment and Decision Environments (NAIADE) method and the chosen alternative is LET-410.

In a study conducted to select a regional aircraft for the fleet of a hypothetical airline company operating in eastern Europe, Dozic and Kalic (2014) use the AHP method. Differing from other studies in aircraft selection, their model includes the qualitative criterion named payment conditions, which is assessed through verbal judgments. The authors choose seven different alternatives to include in their model that fit the seating and range requirements for a forecasted demand of up to 100 passengers and a given route. Among the alternatives which include both turboprop aircraft and regional jets, a turboprop aircraft, ATR 72-600, has the highest score, due to lower operating costs compared to the regional jets, as justified by the authors. The paper also includes a sensitivity analysis, based on the changing importance values of criteria.

Bruno et al. (2015) apply a combination of AHP and fuzzy set theory for an aircraft evaluation case for Air Italy's regional jet requirement. In the study, the requirements of the airline regarding the alternatives are considered, and three regional jets are proposed to be examined. For the criteria determination, aviation literature is used along with the airline's needs, and eight sub-criteria under four main category criteria are used in the study. A focus group involving four experts from Air Italy are consulted to evaluate the importance of criteria and to obtain criteria weights with AHP. The experts are later asked to assess the performance levels of the alternative aircraft based on a linguistic scale. AHP and fuzzy set theory are later combined to rank the alternatives. Although the study introduces environmental impact as one of the main criteria, it ignores several technical characteristics such as, range, seat capacity, and cargo capacity.

Dozic and Kalic (2015b) construct a fleet planning model for a hypothetical airline operating from Belgrade airport, dividing the planning process into fleet composition, fleet sizing and aircraft selection steps. After determining the suitable categories of aircraft for operations to short/medium range routes and the number of aircraft required, the authors use Even Swaps Method to select the alternatives. The authors place the alternatives into two groups as small and medium based on the seat capacities of the aircraft. In the model, five criteria are used for the two groups of alternatives, which are seat capacity, price, maximum take-off weight (MTOW), baggage per passenger, and unit cost. The study finds ATR 72-600 and Airbus A319neo as the best alternatives for the small and medium aircraft, respectively. Dozic and Kalic (2015a) compare the results of Even Swaps Method with AHP for the small aircraft category with the addition of payment conditions criterion. The paper presents the same aircraft as the best alternative.

As an extension to an earlier study, Özdemir and Başlıgil (2016) use fuzzy ANP and generalized Choquet integral methods for Turkish Airline's aircraft selection. The criteria and alternatives used are the same as in Özdemir et al. (2011). The authors justify the usage of these two methods by stating that these methods enable to work with dependencies and interactions among the factors included in the model. For the ANP method, a network of factors of the model, and their inner and outer dependencies are constructed. Later, experts evaluate the factors in pairwise comparisons. In the application of the generalized Choquet integral method, experts are asked to verbally define the importance degrees of criteria and the perceived performances of aircraft. To validate the results of these methods, the authors utilize fuzzy AHP method. Although the prevailing alternative is the same in all three methods, the rankings of the generalized Choquet integral method differs from the rankings of fuzzy ANP and fuzzy AHP methods. As pointed by the authors, a limitation of the study is the complexity arising from high number of pairwise comparisons required from the experts.

Dozic et al. (2018) use fuzzy AHP method for the hypothetical regional airline. After an examination of literature, the authors choose three main criteria (aircraft characteristics, costs, added value indicators) and ten sub-criteria. The authors consult experts from various airlines and academicians to construct pairwise comparisons of the involved criteria. Logarithmic fuzzy preference programming is used to acquire crisp weights from fuzzy evaluations. The aircraft that is selected as best was the same as in the previous work of Dozic and Kalic.

Kiracı and Bakır (2018a) use three different MCDM methods to obtain a ranking of alternatives in an aircraft selection study for airline companies. Seven criteria are identified to be incorporated in the model through literature survey and interviews with aviation sector experts. In the paper, four of the most ordered medium haul aircraft types in 2016 are chosen as alternatives. To acquire criteria weights, the authors use the AHP method and calculate the geometric mean of individual judgments made by experts. To find the rankings of aircraft, Complex Proportional Assessment (COPRAS) and Multi-Objective Optimization Method by Ratio Analysis (MOORA) methods are used, and the same rankings are obtained in both approaches. The authors use the same weights in both approaches.

Ilgın (2019) uses Linear Physical Programming (LPP) and TOPSIS methods for a hypothetical aircraft selection study. The paper presents five criteria and six short-medium range aircraft in its model. In the first part of the study, DMs assess a range of preference values based on desirability levels for each criterion and criteria weights are acquired. For the scoring of alternatives, the deviations of aircraft performance values from the desired preference levels are used along with criteria weights. TOPSIS is also utilized for the same purpose, where directly assigned criteria weights are used, which results in the same rankings with the LPP method. The author states that subjective weight derivation is eliminated through the usage of LPP. However, DMs use subjective assessments when choosing preference values for criteria.

In their study to obtain weights for aircraft selection criteria, Şener and Yılanlı (2019) use DEMATEL method. Through a survey of the literature and with the views of experts, they identify fourteen criteria. The impact of each criterion on other criteria are assessed by experts, which is then used to find criteria weights to be used in aircraft selection problems.

Ahmed et al. (2020) use fuzzy AHP and efficacy methods to select regional aircraft for the short-haul sector in Canada. Under five main categories, fifteen sub-criteria are involved in the study, with five environmental impact sub-criteria specifically selected for Canadian aviation setting. Four regional aircraft are evaluated, which are chosen according to literature survey, demand, and expert views. To be used in combination with efficacy method, fuzzy AHP is employed for the purpose of criteria weights determination. Through the efficacy method, acceptable and unacceptable levels for each criterion are identified by industry experts and academicians, which are then used to calculate the performance scores of the alternatives. The study contains a high number of criteria and some of the sub-criteria involved have weights as low as 1%. The inclusion of unnecessary criteria can be disadvantageous in some settings, as it might increase the complexity and the time required from experts.

Kiracı and Akan (2020) combine fuzzy AHP and fuzzy TOPSIS methods for passenger aircraft selection of commercial airlines under uncertainty. The study investigates the problem with three main criteria, which are technical, economic and environmental aspects, and thirteen sub-criteria. The authors first apply fuzzy AHP method for sub-criteria and eliminate some of these sub-criteria based on their weights. Then, they determine the weights of eight sub-criteria which are selected at the first step through fuzzy AHP procedure. Finally, linguistic assessments of experts are used to determine the performance values of alternatives. Selected from literature, a total of four medium haul alternatives are evaluated, where Airbus A321neo is ranked first.

2.2. Aircraft Selection Criteria

Through examination of the relevant literature, Table 1 is constructed. Table 1 presents the criteria included in this study and previous studies that use these criteria. Criteria names that have the same or similar meaning are demonstrated in parentheses as they appear in the referenced study.

Table 1 Aircraft Selection Criteria References

Criteria	References
Price	Yeh and Chang (2009), Özdemir et al. (2011), Gomes et al. (2012), Dozic and Kalic (2014, 2015a, 2015b), Bruno et al. (2015), Özdemir and Başlıgil (2016), Kiracı and Bakır (2018a), Dozic et al. (2018), Ilgın (2019), Şener and Yılanlı (2019), Kiracı and Akan (2020), Ahmed et al. (2020)
Direct Operating Cost	Yeh and Chang (2009), Gomes et al. (2012) (as “Operating cost”), Dozic and Kalic (2014, 2015a, 2015b) (as “CASM - Cost per available seat mile”), Bruno et al. (2015) (as “Operative costs”), Özdemir and Başlıgil (2016) (as “Operation and spare cost”), Dozic et al. (2018) (as “CASM”), Kiracı and Akan (2020) (as “Operating cost”)

Table 1 (continued)

Range	See et al. (2004), Gomes et al. (2012), Kiracı and Bakır (2018a), Dozic et al. (2018), Ilgın (2019), Şener and Yılanlı (2019), Kiracı and Akan (2020), Ahmed et al. (2020)
Seat Capacity	See et al. (2004), Dozic and Kalic (2015b), Kiracı and Bakır (2018a), Dozic et al. (2018), Ilgın (2019), Şener and Yılanlı (2019), Kiracı and Akan (2020), Ahmed et al. (2020)
Cargo Capacity	Dozic and Kalic (2014) (as "Total baggage"), Kiracı and Bakır (2018a) (as "Maximum payload"), Ilgın (2019) (as "Luggage volume"), Şener and Yılanlı (2019), Ahmed et al. (2020) (as "Payload")
Reliability	Yeh and Chang (2009), Özdemir et al. (2011), Özdemir and Başlıgil (2016)
CO_2 Emissions	Bruno et al. (2015) (as "Environmental pollution"), Kiracı and Bakır (2018a) (as "Amount of greenhouse gas release"), Kiracı and Akan (2020) (as "Pollution")
Noise Level	Yeh and Chang (2009), Bruno et al. (2015), Şener and Yılanlı (2019), Kiracı and Akan (2020), Ahmed et al. (2020) (as "EPNdB")
Cabin Volume per seat	Sun et al. (2011)
Cabin Altitude	-

2.3. Dependency of Criteria in Aircraft Selection Studies

Among the studies that deal with commercial aircraft selection problem using MCDM methods, few mention dependencies of criteria. See et al. (2004) use fuzzy group MCDM and TOPSIS methods, and involve three criteria (number of passengers, cruise range, cruise speed) in their model, which they state are independent of each other. Özdemir et al. (2011) use 10 sub-criteria in their study for the selection of a middle-ranged, narrow body aircraft for Turkish Airlines. To discover the interactions between criteria, they use ANP. Sun et al. (2011) specify a set of attributes for the alternative aircraft, and state that these attributes involve redundant information. They explain this further by stating that the criteria maximum range and MTOW depend on each other, and that these criteria cannot be considered together in MCDM methods. Gomes et al. (2014) use NAIADE method for the problem of choosing a regional charter aircraft for a Brazilian airline company. The authors state in their study that the method does not require preferential independence between criteria, which is pointed as one of the reasons for selecting this method. Özdemir and Başlıgil (2016) use fuzzy ANP and generalized Choquet integral methods to deal with the dependency between criteria as the main contribution of their study. They compare the results of their study with that of fuzzy AHP method, and despite the presented rankings are the same, the alternative scores differ slightly. The difference between the findings are attributed to the assumption of independent criteria in fuzzy AHP method. In their paper, Şener and Yılanlı (2019) uses DEMATEL method to assign priorities for aircraft selection criteria, which is a method based on determination of the interactions among criteria through measures of direct influences between them.

2.4. Application Areas of AHP, DEMATEL and TOPSIS Methods

Since its introduction, the AHP method has been widely used in various fields for the solution of complex decision making problems. Examples of application areas include engineering, management, aviation, finance, government, manufacturing, health care, etc. (Vaidya & Kumar, 2006). Vargas (2010) uses the AHP method for selection of projects in a portfolio for a fictitious business organization where alternatives including opening a new branch, moving to a new location, implementing a new ERP system and others are investigated. In another study conducted by a group of researchers including medical doctors, the focus is on a clinical problem regarding the treatment of a patient (Dolan et al., 1989). The group makes pairwise comparisons between the alternatives using their judgements based on data regarding the cost of treatment, the probabilities of infection and side effects of the treatment strategies. Goossens and Basten (2015) use the AHP method to select a maintenance policy among three alternatives for naval ships.

DEMATEL method has been utilized by researchers for various purposes. These include discovering interdependencies between criteria, finding key criteria, and obtaining dependency criteria weights (Si et al., 2018). Khazai et al. (2013) use DEMATEL method to study the direct and indirect dependencies of selected indicators for their research on vulnerability of regions to disaster losses. They also use the technique to find dependency weights for the selected indicators, which are later combined with expert views to reach overall weights for indicators. Chang et al. (2011) apply fuzzy DEMATEL method to determine key criteria for supplier selection. Seker and Zavadskas (2017) present critical causal factors of occupational hazards in construction industry through fuzzy DEMATEL method.

In the literature, there are a number of studies that combine MCDM methods for selection type studies other than aircraft selection. Pelorus (2017) combines AHP with TOPSIS for the evaluation process of ballast water treatment systems for ships. Ortiz-Barrios et al. (2019) combine AHP with DEMATEL to determine interdependence between the criteria and their priorities to rank food suppliers with TOPSIS. Büyüközkan and Güleryüz (2016) integrate DEMATEL with ANP to select renewable energy resources in Turkey. In a study conducted to select a knowledge management strategy for companies, Wu (2008) uses a combined ANP and DEMATEL approach. Dalalah et al. (2011) use fuzzy DEMATEL to determine criteria weights and later use fuzzy TOPSIS for the selection of cans suppliers.

2.5. Remarks and Contributions

With the extensive literature review discussed in the previous sections, it is presented that MCDM methods are applicable for the passenger aircraft selection problem. As mentioned before, some research gaps in this area are observed. Insight from the literature and research gaps are combined to be addressed in this thesis.

Based on the review of relevant studies, different criteria in aircraft selection problems are identified. While the criteria used differs for varying settings, a set of criteria are observed to be recurring, which are agreed upon by researchers and industry professionals as factors that are influential in aircraft selection. A tendency observed in more recent works is the inclusion of environmental impact criterion, which is consistent with the industry’s standpoint on sustainability.

It is noticed that the number of criteria used in these studies varies between three and fourteen. While a low number of criteria may be incapable of representing the decision making setting, a high number of criteria may overcomplicate the problem. Therefore, for this study, a criteria set is chosen which is observed to have influence in aircraft selection, and is comprehensive without overcomplicating the problem. These criteria are grouped under four main criteria, which are economics, technical characteristics, environmental impact, and passenger comfort.

Among the studies investigated in the literature review, no study presents an IRM of criteria. In this thesis, DEMATEL method is utilized to discover the direct and indirect influences between criteria, construct an IRM, and obtain a set of weights for these dependent criteria. With the addition of an IRM of criteria, it is expected to provide DMs with insight on interactivity between aircraft selection criteria. For the purpose of obtaining the best wide-body aircraft using dependent criteria, DEMATEL method is combined with TOPSIS method. To the best of our knowledge, this is the first study that uses the combined approach of DEMATEL-TOPSIS in aircraft selection problem.

On a side note to the discussion above, the ANP method is also known to be capable of handling dependency of criteria in MCDM settings. However, ANP possesses some limitations which makes its implementation in this study to be inconvenient. Ravi et al. (2005) list several disadvantages of ANP in their paper, one being the requirement of a large number of pairwise comparisons from the experts, which can be time consuming. Apart from the challenging data acquisition part, ANP necessitates more calculations compared to AHP due to the increased number of pairwise comparisons and added matrices. Due to these limitations, ANP was not used in this study.

Regarding the MCDM methods applied for aircraft selection studies, it is seen that AHP and fuzzy AHP methods are used by a number of researchers, either for the aircraft selection problem itself (Bruno et al., 2015; Dozic & Kalic, 2014; Dozic et al., 2018; Özdemir & Başlıgil, 2016), or for derivation of criteria weights in this problem (Ahmed et al., 2020; Kiracı & Akan, 2020; Kiracı & Bakır, 2018a; Sun et al., 2011). In order to provide a means to validate the results of this study and discover the effects of the assumption of independent criteria on the results, AHP method is used in this study for criteria weight determination, to be combined later with TOPSIS method.

It should also be noted that fuzzy numbers are not implemented in this study to avoid unnecessary complexity in the problem. Saaty and Tran (2007) advise against the usage of fuzzy numbers by stating that the use of fuzzy numbers would not aid towards achieving increased validity in solutions, but would rather make the judgments made by experts even fuzzier.

CHAPTER 3

METHODOLOGY

In this chapter, the MCDM methods used in the study are explained thoroughly. These methods are namely AHP, DEMATEL and TOPSIS. After explanation of methods, the two approaches taken in this study are presented. Later, the goal, criteria and alternatives used in this study are discussed.

3.1. AHP Method

AHP is an MCDM method that was developed by Thomas L. Saaty in 1970s. It provides a means to establish priority values for the criteria involved in decision making through measuring by how much one element of the problem dominates the other with respect to a specific criterion, for which expert judgments are used (Saaty, 2008). AHP is a method that can be applied to problems which has a complex nature, involving several tangible and intangible criteria and alternatives. Saaty and Vargas (2012) state that the process requires this complex problem to be broken down into a hierarchy for the purpose of simplification, which is similar to the human mind's approach to a diverse problem. They describe the model as a tool that can capture the rationality and the intuition of the DM.

Saaty (2008) decomposes the decision making process into the following steps. First, the problem is defined with the decision goal in mind. The next step involves construction of a hierarchy that consists of levels from top-to-down: the goal, the criteria (and sub-criteria if present), and the alternatives. Forming pairwise comparison matrices (PCMs) out of homogeneous elements of the hierarchy is the third step defined by Saaty. In pairwise comparisons, elements of a level in the hierarchy is compared with each other with respect to an element in a higher level of the hierarchy.

Finally, priority values acquired through pairwise comparison judgments are used to derive weights for criteria and sub-criteria.

When using judgments made by humans, consistency is an important aspect to be considered. The PCMs have to be coherent up to a degree for results to be valid. The AHP method accounts for consistency by measuring it using the consistency ratio (CR) (Saaty & Vargas, 2012).

The procedure to be followed in applying the method is discussed in more detail in the following steps.

Step 1: Problem definition

A decision problem consists of an overall objective to be achieved, criteria that have an effect on the decision, and alternative solutions to be chosen among. The goal, the criteria (and sub-criteria), and alternatives need to be clearly defined when AHP is to be utilized to solve the problem. Here, the sub-criteria that are categorized under the same criterion need to have common characteristics for these to be able to be compared by the DM.

An important consideration when defining a problem is to determine, to what extent the problem will be defined. The decision making problem may be particular to a single person, a group, or an organization, and although the context and goal of the problem may be similar to another problem, the parties involved in the process may have different interests. As Saaty (1990) mentions, the framework of the problem must contain sufficient details for the problem to be correctly represented, while also bearing in mind the setting of the problem.

Step 2: Hierarchical framework

The complex nature of a decision problem can be dealt with by decomposing the problem and forming a hierarchy. The decomposition is completed so that the hierarchy contains more general elements at the top and more tangible elements at the bottom (Saaty, 1995). This process proves useful to the DM by giving an overview of the relations between the elements of the case, and providing a means to observe whether elements in a level of the hierarchy are of comparable nature (Saaty, 1990).

Figure 1 illustrates a sample decision hierarchy. This sample hierarchy is constructed with four levels, with the goal, criteria, sub-criteria and alternatives at each respective level.

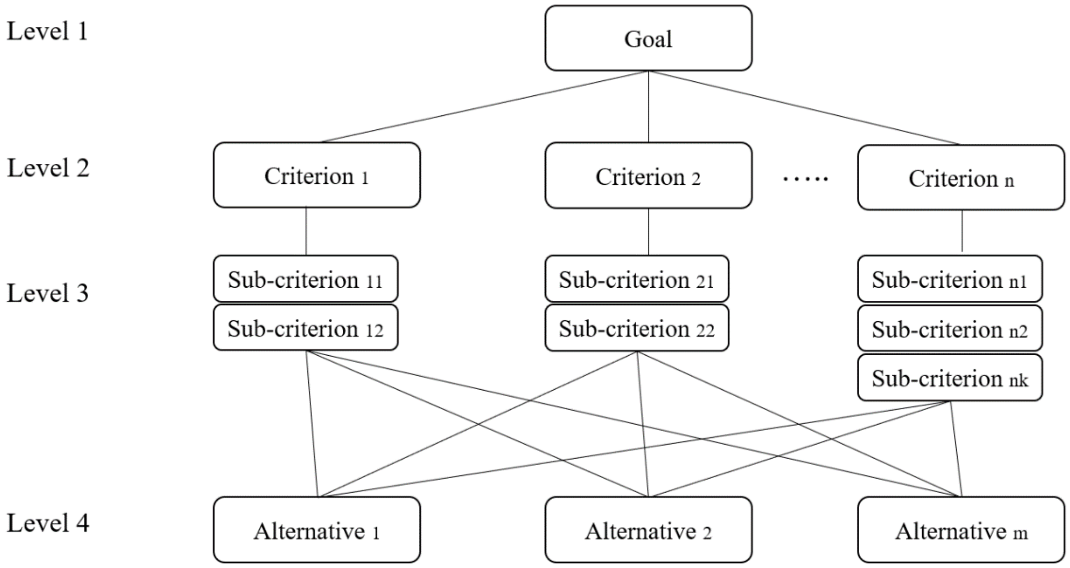


Figure 1 Sample Decision Hierarchy

Step 3: Pairwise comparisons

Once the process of decomposition is completed and the elements of the decision problem have been grouped in clusters according to a common feature, PCMs are built. Pairwise comparisons help detect the relative importance of elements with respect to a shared criterion. When comparing criteria, sub-criteria or alternatives, the DM is asked to judge how much more an element in a pair is important than the other, with respect to an upper level element in the hierarchy.

This measurement of elements requires one to use a scale. To be used along with the AHP, Saaty (1990) presents the fundamental scale, provided in Table 2. When comparing, a number between 1 to 9 is assigned to an element, based on the judgment of the DM. The scale provides verbal definitions and corresponding values, and preferably the verbal statements should be expressed by the DM to assign a number to an element. The DMs should avoid assigning numbers without justification of their views on the relative importance of the pairs (Saaty, 1988).

Table 2 The Fundamental Scale (Saaty, 1990)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

The elements of the hierarchy to be compared in pairs are used to construct PCMs. For n elements, a square matrix of size $n \ x \ n$ is constructed, shown in Eq. (1). An element a_{ij} in the matrix represents the relative importance of element i compared to j, with respect to a higher level element in the hierarchy. Therefore, element a_{ji} attains the reciprocal of the value assigned to a_{ij}, as also shown in Eq. (2).

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{1}$$

$$a_{ij} = {}^{1}/_{a_{ji}} \qquad i,j = 1,2,\dots,n \tag{2}$$

$$a_{ii} = 1 \qquad i,j = 1,2,\dots,n \tag{3}$$

A PCM with n elements to be compared requires the DM to make $n(n-1)/2$ evaluations since the lower triangle of the matrix consists of the reciprocals of pairwise comparisons, and the diagonal elements are equal to one, as shown in Eq. (3).

Step 4: Weight derivation

To derive the weights of the main criteria and the local weights of the sub-criteria, PCMs are used. A method suggested by Saaty to obtain the vector of weights of the criteria is the eigenvector method. The method requires solving Eq. (4), where A indicates the PCM, w indicates the right eigenvector of A, and λ_{max} is the maximum eigenvalue of A.

$$A \cdot w = \lambda_{max} \cdot w \tag{4}$$

The exact value of the eigenvector of A, which is the vector of priorities (weights), can be acquired through certain matrix calculations. However, to avoid complexity in calculations, an approximation of the eigenvector suggested by Saaty and Vargas (2012) is used in this study. The approximation involves normalizing each column element of matrix A, and taking the average of each row of the normalized PCM. The resulting vector is the weight vector, w, shown in Eq. (5). The total of all the weights of a group of criteria equals to 1, as shown in Eq. (6).

$$w_i = (w_1, w_2, \dots, w_n) \tag{5}$$

$$\sum_{i=1}^{n} w_i = 1\,, \qquad i = 1, 2, \dots, n \tag{6}$$

Step 5: Consistency check

Pairwise comparisons of criteria may involve inconsistencies in judgments. To detect the level of consistency of judgments, AHP incorporates the consistency index (CI) presented in Eq. (7), where λ_{max} is the maximum eigenvalue, and n is the dimension of the PCM. Consistency check is performed by calculating CR as shown in Eq. (8). Table 3 provides random consistency index (RI) values, which are acquired through a large number of randomly generated matrices by averaging the CI values of these matrices.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{7}$$

$$CR = \frac{CI}{RI} \tag{8}$$

Table 3 RI Values

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Consistency check is an essential step of the process, which is an indicator of the preciseness of the derived weights. For the results to be valid though, the matrix need not be entirely consistent, since Saaty (1983) states that CR values of 0.10 and below are of acceptable levels of inconsistency, and CR values below 0.20 are tolerable. If the value of CR is greater than tolerable, the pairwise comparisons should be reviewed by the DM to improve the consistency of the judgments.

Step 6: Derivation of global weights

Once the weights of main criteria and local weights of sub-criteria are derived, the global weights of the criteria can be calculated. This requires the multiplication of each sub-criterion local weight with its corresponding main criterion weight.

3.2. DEMATEL Method

DEMATEL is an MCMD method developed in Geneva Research Center of the Battelle Memorial Institute. The method is particularly useful for complex problems involving criteria that have interdependencies, enabling the users to measure the influences of one criterion over another, and distinguish the criteria into cause and effect groups (Si et al., 2018). DEMATEL also supports the DMs visualize causal relationships among criteria with an IRM (Wu & Lee, 2007). The method is also capable of revealing key criteria through the IRM (Si et al., 2018).

Following are the steps of the DEMATEL method (Si et al., 2018; Wu, 2008):

Step 1: Direct relation matrix

The direct influence of criterion i on criterion j is measured through a comparison scale that classifies the level of influence from 0 to 4: 0 (no influence), 1 (low influence), 2 (medium influence), 3 (high influence), 4 (very high influence). Through pairwise comparisons, direct relation matrix (DRM) A' of size $n \ x \ n$ is formed, where n is the number of criteria and a'_{ij} represents the direct influence of criterion i on criterion j.

Step 2: Normalized direct relation matrix

DRM A' is normalized with the following equations (9) and (10) to attain X, which is the normalized DRM:

$$X = k \cdot A' \tag{9}$$

$$k = \frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} a'_{ij}}, \qquad i, j = 1, 2, \ldots, n \tag{10}$$

Step 3: Total relation matrix

The total relation matrix (TRM) T is obtained through Eq. (11) using the normalized DRM X acquired in the previous step, where I denotes the identity matrix. Elements of the TRM incorporate both the direct and indirect influences a criterion exerts on other criteria, and is used to identify the strength of the influence.

$$T = X(I - X)^{-1} \tag{11}$$

Step 4: Forming an IRM

The sum of rows and the sum of columns of the TRM are represented by the vectors D and R, respectively, shown in equations (12) – (14). Here, t_i represents the i^{th} row sum in matrix T, and shows the sum of direct and indirect effects that criterion i has on other criteria. On the other hand, t_j represents the j^{th} column sum in the matrix T, and shows the sum of direct and indirect effects that criterion j receives from other criteria.

$$T = \left[t_{ij}\right]_{nxn}, \qquad i, j = 1, 2, \dots, n \tag{12}$$

$$D = \left[\sum_{j=1}^{n} t_{ij}\right]_{nx1} = [t_i]_{nx1} \tag{13}$$

$$R = \left[\sum_{i=1}^{n} t_{ij}\right]_{1xn} = \left[t_j\right]_{nx1} \tag{14}$$

When $i = j$, the sum $(D_i + R_i)$, which is defined as “Prominence”, becomes an indicator of the direct and indirect effects that are given and received by criterion i. This may be interpreted as the degree of importance that criterion i holds. In a similar manner, $(D_i - R_i)$, defined as “Relation”, shows the net effect that criterion i has. When the value of $(D_i - R_i)$ is positive, criterion i is classified in the cause group. Conversely, when the value of $(D_i - R_i)$ is negative, criterion i is classified in the effect group.

Using the $(D+R)$ and $(D-R)$ values obtained for each criterion, an IRM may be constructed, where $(D+R)$ values represent the horizontal axis, and $(D-R)$ values represent the vertical axis. By enabling the DMs to visualize the extent of interrelationships between the criteria and determine important criteria, the IRM becomes an effective instrument in the decision making process (Si et al., 2018; Tzeng & Huang, 2012).

Step 5: Threshold value calculation

As discussed, the elements of the TRM represent the strength of the influence between two criteria, where higher values indicate stronger influences. That is, the influence of criterion i on criterion j that has a value greater than that of another interaction, corresponds to a stronger influence (Sara et al., 2015).

In order to map only the significant relations between criteria in the IRM and avoid complexity when analyzing the interactions, a threshold value is used. Elements of the TRM that have values greater than the threshold value are shown in the IRM with arrows originating from the criterion that exerts the influence on another criterion. Threshold value can be specified by the DMs, or can be calculated with Eq. (15) (Sara et al., 2015; Si et al., 2018), where N denotes the number of elements in the TRM.

$$\alpha = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij}}{N} \tag{15}$$

The influences between criteria whose values exceed the threshold value can be further separated from other interactions observed in matrix T in order to show the strength of the influence. For this purpose, influences can be depicted with thick or thin arrows based on their values (Chang et al., 2011).

Step 6: Criteria weight calculation

As previously mentioned, DEMATEL method provides a means to assess the importance of a criterion through the summation of the direct and indirect influences that are given and received by that criterion. In the literature, this fact has been used by some researchers to determine dependency weights of criteria.

Several studies utilize one of the approaches for calculating weights with DEMATEL method, which involves using the “Prominence” and “Relation” values of a criterion (Dalalah et al., 2011; Pamučar & Ćirović, 2015). In this approach, values obtained with Eq. (16) are normalized through Eq. (17), and w'_i is the weight calculated for criterion i.

$$W'_i = \sqrt{(D_i + R_i)^2 + (D_i - R_i)^2} \tag{16}$$

$$w'_i = \frac{W'_i}{\sum_{i=1}^{n} W'_i} \tag{17}$$

3.3. TOPSIS Method

TOPSIS is an MCDM method that was developed by Hwang and Yoon (1981). TOPSIS makes it possible to order alternatives according to their distances from the positive and negative ideal solutions. In this regard, the alternative to be ranked first should have the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution.

The method has several advantages that prove useful in MCDM problems, such as its rationality, comprehensibility, and simplicity (Roszkowska, 2011). Moreover, the amount of subjective input required from DMs is minimal, with the method requiring only weights to be assigned to criteria (Olson, 2004), making the method suitable for problems with numerical data. In this thesis, criteria weights to be used in the implementation of TOPSIS method are obtained through AHP and DEMATEL methods.

The procedure of the method is explained as follows (Hwang & Yoon, 1981; Triantaphyllou, 2000):

Step 1: Construct the decision matrix

The decision matrix (D') is established with elements representing the evaluations of m alternatives corresponding to n criteria, shown in Eq. (19). In matrix D', d'_{ij} denotes the performance value of i^{th} alternative with respect to j^{th} criterion, where $i = 1, 2, \dots, m; j = 1, 2, \dots, n$.

$$D' = \begin{bmatrix} d'_{11} & d'_{12} & \cdots & d'_{1n} \\ d'_{21} & d'_{21} & \dots & d'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d'_{m1} & d'_{m2} & \cdots & d'_{mn} \end{bmatrix} \tag{19}$$

Step 2: Calculate the normalized decision matrix

The performance values present in the decision matrix may have varying units. To enable comparison across values, the decision matrix elements need to be non-dimensional. For this purpose, the performance values are normalized with Eq. (20), where r'_{ij} represents the normalized value of d'_{ij}. The resulting matrix is the normalized decision matrix, R'.

$$r'_{ij} = \frac{d'_{ij}}{\sqrt{\sum_{i=1}^{m} (d'_{ij})^2}} \tag{20}$$

Step 3: Calculate the weighted normalized decision matrix

Using the weights derived by AHP or DEMATEL methods, the weighted normalized decision matrix (V) can be formed through the multiplication of the columns of matrix R' with the corresponding weight for each criterion. Shown in Eq. (21), v_{ij} denotes the weighted normalized value, and w_j is the weight of criterion j, where $\sum_{j=1}^{n} w_j = 1$.

$$v_{ij} = w_j \cdot r'_{ij} \tag{21}$$

Step 4: Determine positive ideal and negative ideal solutions

To determine the positive ideal and the negative ideal solutions, the criteria are separated into benefit (larger is better) and cost criteria (smaller is better). The positive ideal solution comprises of the maximum values for the benefit criteria and the minimum values for the cost criteria. The negative ideal solution, on the other hand, comprises of the minimum values for the benefit criteria and the maximum values for the cost criteria.

The artificially created alternatives A^+ and A^- represent the positive ideal and the negative ideal solutions, respectively, and are defined in equations (22) and (23).

$$A^+ = (v_1^+, v_2^+, \ldots, v_n^+) = \left(\left(\underset{i}{max}\, v_{ij} \middle| j \in J\right), \left(\underset{i}{min}\, v_{ij} \middle| j \in J'\right)\right) \tag{22}$$

$$A^- = (v_1^-, v_2^-, \ldots, v_n^-) = \left(\left(\underset{i}{min}\, v_{ij} \middle| j \in J\right), \left(\underset{i}{max}\, v_{ij} \middle| j \in J'\right)\right) \tag{23}$$

where $i = 1, 2, \ldots, m, J$ is associated with the benefit criteria, and J' is associated with the cost criteria.

Step 5: Calculate the distances

The distances of alternatives from the positive ideal solution and the negative ideal solution are calculated using the Euclidean distance as defined in equations (24) and (25), where S_i^+ identifies the distance of i^{th} alternative from the positive ideal solution and S_i^- identifies the distance of the alternative from the negative ideal solution.

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2}, \quad i = 1, 2, \ldots, m \tag{24}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}, \quad i = 1, 2, \ldots, m \tag{25}$$

Step 6: Calculate the relative closeness to the ideal solution

The relative closeness of i^{th} alternative with respect to A^+ is calculated as defined in Eq. (26). It can be observed from the definition of C_i, that the higher the value of C_i, the closer an alternative is to the ideal.

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-}, \quad 0 \le C_i \le 1, \quad i = 1, 2, \dots, m \qquad (26)$$

Step 7: Rank the preference order and determine the best alternative

The alternatives are ranked in a descending order according to their C_i values in order to obtain the best alternative.

3.4. AHP-TOPSIS Approach

The first approach used in this study involves the AHP and TOPSIS methods. With the AHP method, the criteria weights are attained through pairwise comparisons made by experts. Later, these weights are used in TOPSIS method to obtain the scores of alternatives. The ranking of the alternatives according to their scores reveals the best alternative for the AHP-TOPSIS approach.

The AHP method has several aspects that makes it suitable in this setting. One of the reasons for selecting this method was due to its convenience in application. The method is relatively straightforward to use and comprehend (Kahraman et al., 2003), which is also recognized among experts. Further, the AHP and fuzzy AHP methods have been applied by various researchers in the aircraft selection problem before. Several researchers use AHP and fuzzy AHP methods for the aircraft selection problem (Bruno et al., 2015; Dozic & Kalic, 2014; Dozic et al., 2018; Özdemir & Başlıgil, 2016), whereas some use these methods to determine weights of criteria in aircraft selection studies (Ahmed et al., 2020; Kiracı & Akan, 2020; Kiracı & Bakır, 2018a; Sun et al., 2011). The usage of these methods in previous aircraft selection studies may enable a comparison to be made across the approaches used in this study.

It should be noted here, that AHP is not a method that can be used to detect and handle dependencies between criteria (Wu and Tsai, 2012). However, it has been used in the studies referred above for the aircraft selection problem before. Considering the similarities between the criteria used in the studies mentioned above with the proposed criteria in this study, an assumption of independent criteria may be justified for the purpose of comparing AHP-TOPSIS results with another MCDM approach, DEMATEL-TOPSIS, for the validity of the results of this study.

3.5. DEMATEL-TOPSIS Approach

As discussed, the AHP method is unable in detecting interactions between criteria and requires the assumption of criteria independency to be used in this research problem. Therefore, to be able to deal with dependency among criteria, DEMATEL method is used in this study. Through this method, assessments of experts on the strength of direct influences between criteria makes it possible for the user to get a grasp of the direct and indirect influences a criterion gives and receives. Further, the division of criteria into cause and effect groups, and the formation of an IRM can let the user visualize the interdependencies between criteria. The main reason of the implementation of DEMATEL method in this study, however, is that it helps derive dependency weights of criteria, which are used along with TOPSIS method. With the TOPSIS method, the alternatives of the aircraft selection problem are ranked with respect to their scores, and the aircraft with the highest score is chosen as the best alternative of this approach.

3.6. Criteria Definitions

3.6.1. Economics

The airline industry is a sector in which profit margins are relatively low with an industry average earnings before interest and taxes margin of 5.2% in 2019 (IATA, 2021a). This, along with the fact that purchasing an aircraft is a major investment for airlines makes economics a key criterion. Various components constitute economics criterion in different settings, such as price, payment conditions, financial costs, salvage value, maintenance cost, crew costs and operation costs. The main components of economics criterion are common in the aircraft selection context.

The life cycle cost of an aircraft involves the aircraft price, the direct operating cost (DOC), and the indirect operating cost (Johnson, 1990). Among these, the aircraft price and DOC are directly related to the aircraft type, whereas the indirect operating cost depends on the airline’s operations. Therefore, in this study, two criteria are selected to represent the economics criteria, which are the price and the DOC of the aircraft. It should be noted that the proposed model considers the selected aircraft will be bought, not leased.

3.6.1.1. Price

Price criterion refers to the passenger aircraft's list price defined by the manufacturers of the aircraft. Generally, as airlines negotiate with the manufacturers for the aircraft to be purchased, they are presented with discounted prices. However, the presented data for the price criterion is obtained directly from the manufacturers and it was assumed that no discounts would be provided to the airline purchasing the aircraft for simplicity.

3.6.1.2. DOC

The DOC is an essential cost component in the daily operations of an airline which involve all costs associated with the operation of the aircraft. An aircraft that has a low DOC is a key for increased profitability. As described by ICAO, the operating cost components of the aviation industry consist of crew, fuel, maintenance, and ownership costs (ICAO, 2017a). Although it is an important metric, gathering type specific data on aircraft is difficult since it has various parameters and these can change from one airline to another. However, to obtain DOC of aircraft several different methods exist. Among these, the method developed by the Association of European Airlines (AEA) is used in this study.

Since the alternatives studied in this study involve long-range widebody aircraft, the method developed by AEA for long-range aircraft (AEA, 1987) is used. In the AEA method, the cost components included are financial cost, crew cost, charges and fees, maintenance cost, and fuel cost. Total financial cost includes depreciation, interest, and insurance. The AEA method uses parameters such as the utilization (number of trips in a year), manufacturer's study price and spares prices, and assumes a 14-year usage period for an aircraft, 5% annual interest rate, and an insurance rate of 0.5%. Total crew cost includes cockpit and cabin crew costs, where the cabin crew costs depend on the number of passengers onboard. Charges and fees include the navigation charges, which are costs related with the usage of air navigation facilities and services; the landing fees, which are paid to the airport authority; and ground handling charges. Total maintenance cost involves airframe and engine maintenance costs; where the airframe maintenance cost depends on the airframe weight and the flight time, and the engine maintenance cost depends on certain engine parameters. Finally, the total fuel cost is calculated with a fuel price of 0.60 \$/kg for an approximate amount of fuel required for a flight distance of 4,345 nautical miles (nm).

The equations and parameters used in the calculation of DOC are presented in the following sections and are based on the publication of AEA (1987). Data sources are provided in Table 8. The unit of DOC in this calculation is \$/block hour. For the calculations, it is assumed that a flight is to be operated from Istanbul, and the distance and flight time data of a flight from Istanbul to New York is used. The flight time for this flight is taken as 10 hrs. The block time, which includes the time to taxi in addition to the flight time, is taken as 10.25 hrs. The distance for this flight is taken as 4,345 nm.

Utilization

To calculate DOC, utilization, or number of trips in a year is calculated first. Utilization is calculated with Eq. (27). In this equation, $t_{available}$ represents the available hours per year, t_{block} represents the block time for the studied flight, and TAT represents the turnaround time, which is the time it takes to prepare the aircraft for departure after its arrival at the destination. The data for $t_{available}$ and TAT were obtained for the flight distance of 4,345 nm, and correspond to 6,500 hrs and 3 hrs. Utilization (U) is measured in hours.

$$U = \frac{t_{available}}{t_{block} + TAT} \tag{27}$$

Total Financial Cost

Total financial cost (TFC) equals to the summation of depreciation (DEPR), interest (INT), and insurance (INS) costs. To calculate these items, total investment cost (TI) is calculated first.

TI, shown in Eq. (28), is the total of the manufacturer’s study price (MSP), airframe spares (AFS), and spare propulsion units (SPU). For MSP, list prices of the aircraft are used. The cost components included in TI are in \$M.

$$TI = MSP + AFS + SPU \tag{28}$$

AFS and SPU are calculated through equations (29) and (30). Here, ENP denotes the engine price and n_e denotes the number of engines, which is set to 2 for all alternatives considered in this study. As data for engine list prices are not available, an approximation of ENP proposed by Vasconcelos Oliveira (2015) was used. Presented in Eq. (31), the approximation calculates ENP in \$M as a function of T_{sl}, which is the maximum thrust of the engine at sea level in kN.

$$AFS = 0.10 \cdot (MSP - ENP \cdot n_e) \tag{29}$$

$$SPU = 0.30 \cdot ENP \cdot n_e \tag{30}$$

$$ENP = (0.0619 \cdot T_{sl} + 3.0951) \cdot 10^6 \tag{31}$$

After obtaining the total investment cost (TI), DEPR, INT and INS values are calculated with equations (32) through (34). These cost items are divided by t_{block}.

$$DEPR = \frac{TI}{14 \cdot U \cdot t_{block}} \tag{32}$$

$$INT = 0.05 \cdot \frac{TI}{U \cdot t_{block}} \tag{33}$$

$$INS = 0.006 \cdot \frac{MSP}{U \cdot t_{block}} \tag{34}$$

Finally, TFC is calculated as shown in Eq. (35):

$$TFC = DEPR + INT + INS \tag{35}$$

Total Crew Cost

Cockpit crew cost (PC) and cabin crew cost (CC) constitute total crew cost (TCC). Although pilot and cabin crew wages vary from one airline company to other and may change based on certain circumstances, approximate hourly rates are used based on values from literature. PC is equal to 350 \$/block hour and CC is calculated with Eq. (36). In CC calculation, n_c stands for the number of cabin crew members and is calculated by dividing the passenger capacity of the aircraft by 35. A rate of 60 \$/block hour was used for cabin crew wages. TCC is presented in Eq. (37).

$$CC = 60 \cdot n_c \tag{36}$$

$$TCC = PC + CC \tag{37}$$

Total Charges and Fees

Total charges and fees (TCF) are the summation of navigation charges (NC), landing fees (LF), and ground handling charges (GHC). For the calculation of LF, MTOW of the aircraft is used in Eq. (38). NC is calculated with Eq. (39), where two parameters, flight distance (d) and MTOW are used. GHC is calculated through Eq. (40) with the payload value of the aircraft. Unit for the flight distance is km, and the unit for MTOW and payload is metric tons.

$$LF = \frac{(6 \cdot MTOW)}{t_{block}} \tag{38}$$

$$NC = \left(0.17 \cdot d \cdot \sqrt{\frac{MTOW}{50}}\right) / t_{block} \tag{39}$$

$$GHC = \frac{(103 \cdot Payload)}{t_{block}} \tag{40}$$

Equation (41) presents TCF:

$$TCF = LF + NC + GHC \tag{41}$$

Airframe Maintenance Cost

Airframe maintenance cost (AMC) has two components, which are airframe labor cost (AFL) and airframe material cost (AFM).

AFL is calculated with Eq. (42). In this equation, W_{af} denotes the airframe weight in metric tonnes, t_f denotes the flight time in hours, and R_l denotes the labor rate of mechanics and technicians, which was taken as \$32.06/hour, as published by U.S. Bureau of Labor Statistics (2021).

$$AFL = \left(0.09 \cdot W_{af} + 6.7 - \frac{350}{W_{af} + 75}\right) \cdot \left(0.8 + 0.68 \cdot t_f\right) \cdot \frac{R_l}{t_{block}} \tag{42}$$

AFM is obtained through Eq. (43), where AFP is the airframe price in \$M, which is calculated by subtracting the engine price from the list price of the aircraft.

$$AFM = AFP \cdot \frac{\left(4.2 + 2.2 \cdot t_f\right)}{t_{block}} \tag{43}$$

Equation (44) shows the calculation of AMC:

$$AMC = AFL + AFM \tag{44}$$

Engine Maintenance Cost

Engine maintenance cost (EMC) is the summation of engine maintenance labor cost (EML) and engine maintenance material cost (EMM). For EML and EMM calculations, parameters related to engine specifications are used. These parameters include T_{sl}, bypass ratio (BPR), overall pressure ratio (OPR), number of compressor stages (n_{cs}), C_1, C_2, and C_3. The last three are calculated with equations (45) through (47):

$$C_1 = 1.27 - 0.2 \cdot BPR^{0.2} \tag{45}$$

$$C_2 = 0.4\left(1 + \left(\frac{OPR}{20}\right)^{1.3}\right) \tag{46}$$

$$C_3 = 0.57 + 0.032 \cdot n_{cs} \tag{47}$$

EML and EMM are shown in Eq. (48) and Eq. (49), respectively:

$$EML = 0.21 \cdot R \cdot C_1 \cdot C_3(1 + T_{sl})^{0.8} \tag{48}$$

$$EMM = 2.56 \cdot (1 + T_{sl})^{0.4} \cdot C_1(C_2 + C_3) \tag{49}$$

EMC is calculated with Eq. (50):

$$EMC = n_e \cdot (EML + EMM) \cdot \frac{\left(t_f + 1.3\right)}{t_{block}} \tag{50}$$

Total Maintenance Cost

Total maintenance cost (TMC) is the total of two cost items: airframe maintenance cost (AMC) and engine maintenance cost (EMC):

$$TMC = AMC + EMC \tag{51}$$

Fuel Cost

The last component in DOC calculation is fuel cost (FC). It is calculated by multiplying the fuel price and the block fuel (F_{block}). Fuel price is obtained from IATA Jet Fuel Price Monitor web page as 0.60 $/kg (IATA, 2021b). Block fuel is the total amount of fuel used for the studied flight distance in kg, and is calculated using Eq. (52). It should be noted that fuel burn data is type specific and is calculated as described in Section 3.8.3. FC is presented in Eq. (53).

$$F_{block} = Fuel\ Burn \cdot Flight\ Distance \tag{52}$$

$$FC = \frac{Fuel\ Price \cdot F_{block}}{t_{block}} \tag{53}$$

Total DOC

Finally, DOC is calculated using Eq. (54):

$$DOC = TFC + TCC + TCF + TMC + FC \tag{54}$$

3.6.2. Technical Characteristics

Technical characteristics criterion is composed of key operational criteria, namely: range, seat capacity, cargo capacity, and reliability. This main criterion represents the operational capability of an aircraft, which effects an airline's both day-to-day businesses and long term, i.e., strategic decisions. That is, an airline may have the options of serving its destinations non-stop or with stops; with more direct routes or longer routes; with lower flight frequencies or higher ones, which are mostly based on the technical capabilities of its fleet, when economic factors are left aside.

3.6.2.1. Range

Range is defined as the maximum distance an aircraft can travel from the departure point to a destination. Setting aside environmental factors, an aircraft's range for a specific number of passengers and amount of cargo can be determined by the payload-range diagram specific to that aircraft. Basically, decreasing the amount of payload makes it possible to increase the range. In this study, however, range criterion refers to the maximum range an aircraft can fly with the maximum number of passengers for a typical two-class seating, as given by the manufacturers. Range is also a decisive criterion for long term plans of an airline, for instance, deciding on new destinations to be serviced. The unit of range in this study is chosen as nm.

3.6.2.2. Seat Capacity

Seat capacity of an aircraft is another important metric for the DMs as it is directly related to the revenue an airline generates. As airlines try to match demand and supply, choosing the aircraft with the right seat capacity to be ordered becomes even more important since the lead times can reach years and future demand is unclear.

The maximum number of passengers an aircraft type can accommodate is based on factors such as safety, range, cargo capacity, legroom, seat widths, classes, etc. The general practice in the industry is not to go for the maximum seats, but to balance the needs of airlines accordingly with the aforementioned factors. Usually, aircraft manufacturers provide two or three-class typical seating capacities, with classes separated for different customer segments as first, business and economy classes. To achieve an easier comparison in this study, two-class typical seating capacities are used for this criterion, for which the data are obtained from the manufacturers.

3.6.2.3. Cargo Capacity

Cargo refers to the freight, baggage and mail that can be carried in the cargo compartments of the aircraft. Despite the fact that only 1% of goods carried around are air cargo in terms of weight, the value of these goods equal 35% of all trade around the world (Boeing, 2021a). IATA (2020) estimates in its World Air Transport Statistics 2020 report, that 44% of the total freight tonnes was carried by mixed operations, meaning operations that include the transfer of both passengers and cargo.

Although the airline industry has undergone a serious setback due to the COVID-19 pandemic, air cargo has proved to be a vital part of transportation of goods, especially for medical supplies. Boeing (2021a) forecasts in its Commercial Market Outlook 2021-2040, that air cargo market will expand by an average annual rate of 4% in the following 20 years. These facts emphasize the value of cargo capacity as a criterion to be considered when selecting a passenger aircraft.

Cargo capacity may be given both as a volumetric capacity and in terms of unit load devices (ULD) that can be carried. ULDs can be either pallets or containers that are made out of aluminum, and they allow for faster ground operations, saving time. The unit for cargo capacity criterion in this study is chosen as ULDs, namely LD3, which is a container type that can hold 4.5 m^3 of cargo, and is compatible with Airbus and Boeing wide-body aircraft.

3.6.2.4. Reliability

For an aircraft to carry out operations in a safe manner, its engines and systems need to be reliable throughout the flight. In the wide-body aircraft selection context, it is proposed by this study to assess the reliability of an aircraft with the aircraft’s Extended Range Twin-engine Operations Performance Standards (ETOPS) rating.

ETOPS is an acronym that was created by ICAO. It is used to identify flight operations of twin-engine aircraft whose flight path include a point that is beyond 60 minutes flight time to a suitable airport at one-engine inoperative speed (ICAO, 2017c). ETOPS certified aircraft obtain ratings for certain durations such as 120 min, 180 min, beyond 180 min, etc. To give an example, an ETOPS-180 rated aircraft is capable of flying along routes that are 180 minutes further than a suitable airport, at its one-engine inoperative speed.

Twin-engine aircraft, including those to be considered in this study, are normally limited to 60 minutes flying time to a suitable airport with one-engine inoperative (ICAO, 2017c). Until 1980’s, this rule restricted airlines to plan routes that were sub-optimal and economically nonviable. However, with the advancements in airframe and engine technologies, ETOPS emerged in 1985. With the introduction of ETOPS certifications, airlines were able to reduce flight distances and flight times, increasing their operational effectiveness.

Figure 2 depicts two flight paths, where the green line represents the ETOPS flight path and the blue dashed line represents the non-ETOPS flight path (Federal Aviation Administration [FAA], n.d.-a). Alternate airports refer to those airports which the aircraft may divert to in case of an in-flight emergency, such as an engine loss (ICAO, 2017c). It should be noted that ETOPS operations both apply to routes overseas and land where the number of alternate airports in the vicinity of the route is scarce.

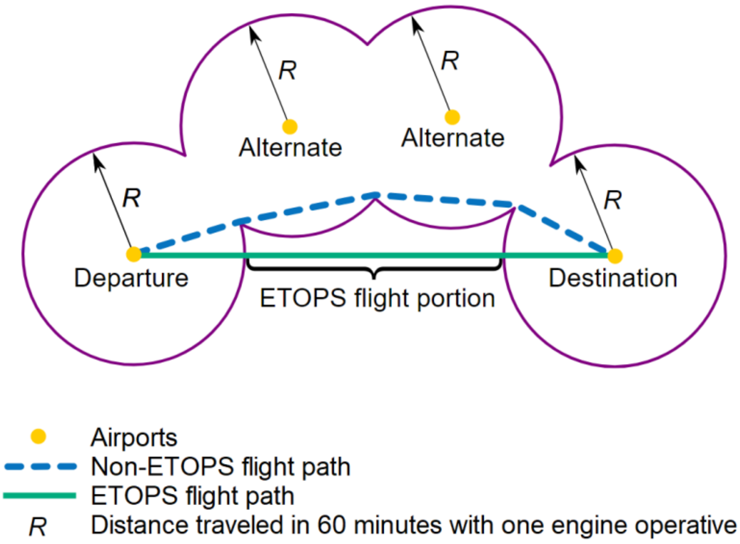


Figure 2 ETOPS and Non-ETOPS Flight Path (FAA, n.d.-a)

ETOPS certification is a two-phase process, which requires both the aircraft type design and the operator of the aircraft to be compliant with the regulations set by the authorities. After the aircraft type receives its ETOPS certification, the operator must be approved for ETOPS. The certification requires aircraft systems to be of high redundancy and the engine to be highly reliable, demonstrating an in-flight shutdown rate less than 0.01 per 1,000 engine hours for an ETOPS rating of beyond 180 mins for instance (ICAO, 2014). On the other hand, the operator that is to apply for an ETOPS certification is required to have adequate capabilities and practices regarding the operation (ICAO, 2014). It is worth noting that certain operators have been known to pursue ETOPS maintenance programs for the increased reliability and performance that the aircraft benefit, although not having required an ETOPS certification for their routes (Boeing, 1999).

ETOPS certification is an indicator of reliability, redundancy and safety of the aircraft type. As it is closely linked to reliability of airframe and propulsion systems of a twin-engine aircraft, ETOPS rating is intended to reflect the reliability of alternatives in this study. The unit of comparison used in this study for reliability is minutes.

3.6.3. Environmental Impact

The aviation industry has two major environmental impacts that are considered in this study: CO_2 emissions and noise pollution. The effects of environmental impacts have been a rising concern for years in the aviation industry. Accordingly, the industry stakeholders have been working towards reducing both carbon emissions and noise levels. The advancement of engine technologies throughout the years and certain operational practices have played a significant role in reduction of these. The aircraft manufacturers also promote the improvements in their aircraft regarding decreased CO_2 emissions and noise levels (Airbus, 2021b; Boeing, n.d.-c); thus, it is convenient to include these as sub-criteria under the environmental impact criterion.

3.6.3.1. CO_2 Emissions

Having relied mainly on fossil fuels from the beginning of the first flight in 1903, the aviation industry has been a significant contributor of greenhouse gas emissions, which are known to cause climate change. According to data provided by U.S. Environmental Protection Agency (2021), CO_2 is the most prevalent greenhouse gas emitted to the atmosphere. CO_2 is the end result of combustion of fuel in engines. Determined by the chemical reaction, the combustion of 1 kg of kerosene results in approximately 3.15 kgs of CO_2 (Lufthansa, 2019).

The aviation industry contributes approximately 2% of total CO_2 emissions (Lund et al., 2017). Although the COVID-19 pandemic caused a substantial decrease in flights and thus CO_2 emissions, global air transportation is expected to reach 2019 numbers by 2023, and experience an average growth rate of 3.2% between 2021 and 2039 (IATA, 2021a). This forecasted growth rate is anticipated by the industry, though it is an indication of increased demand for fossil fuels and increased greenhouse gas emissions in the near future.

To lower the amount of CO_2 emissions generated by the industry, IATA set several targets in 2009 to reduce CO_2 emissions (IATA, 2019). The first of the targets set for the airlines was to improve fleet fuel efficiency by 1.5% per year, until 2020. This target was coupled with another target set for the year 2020, in which carbon neutral growth was aimed. The third target that is adopted by airlines involves reducing net CO_2 emissions in civil aviation to half of 2005 values by 2050. To achieve these targets, the airline industry approaches this problem from various perspectives. Along with certain improvements in aircraft operations and carbon offsetting programs, the efforts to achieve the goals set by IATA are supported by technological improvements in aircraft engines as well (IATA, n.d.).

It is noteworthy to mention that CO_2 is not the only product of the combustion of jet fuel. The chemical reaction of burning kerosene also causes the release of several other products which are contributors to climate change and environmental pollution, such as carbon monoxide, nitrogen oxides, unburned hydrocarbons, and others (Braun-Unkhoff et al., 2017). However, for simplicity, only the emission of CO_2 is used as a sub-criterion to represent greenhouse gases in this study.

As discussed, the issues of climate change and carbon emissions are given serious consideration by airlines. This fact makes CO_2 emissions an important metric to be included as a sub-criterion in this study. The unit of comparison for CO_2 emissions is selected as kilograms per 100 passenger kilometers (kg/100 km per pax), which represents the amount of CO_2 emitted in kilograms, for one passenger in 100 kilometers.

3.6.3.2. Noise Level

Aircraft noise can be classified into three categories with respect to its source: engine noise, aerodynamic noise, and aircraft systems noise. Among these, the noise originating from the engines and the aerodynamic noise produced due to the flow of air around the airframe are the major contributors to the noise signature of the aircraft.

Due to its impacts, aircraft noise is regarded to be an important subject for the environment.

The noise generated by the aircraft is particularly an issue for both humans and wildlife. Studies show that prolonged exposure to noise produced by aircraft can be detrimental to health, causing stress, hypertension (Black et al., 2007), sleep deprivation, tiredness, and headaches (Franssen et al., 2004). Communities living near airports are especially vulnerable to these health problems due to increased proximity to aircraft noises generated during take-off, approach, and landing phases of a flight. Accordingly, mitigation of aircraft noise is regarded as an important matter in the airline transportation business.

The industry wide effort to manage the noise produced by aircraft is led by ICAO, which see the subject as a key priority (ICAO, n.d.-a). A set of standards and recommended practices were set by ICAO, with the introduction of Annex 16 – Volume I document in 1970s. ICAO sets the standards for maximum noise levels for aircraft based on maximum certificated take-off mass, and aircraft noise certification measurement points (ICAO, 2017b). Furthermore, Annex 16 – Volume I introduces a noise evaluation measure, defined as effective perceived noise level, which is intended to measure human sensitivity to noise, and incorporates the level, frequency, and duration of the noise. To determine if an aircraft is eligible for a noise certification, it has to be tested for compliance with the limitations set by ICAO. The noise of the aircraft is measured at three different measurement points during the tests, which are classified as approach, lateral and flyover, based on the position relative to the runway (ICAO, 2017b). The measurement locations for aircraft noise can be seen in Figure 3 (ICAO, n.d.-c).

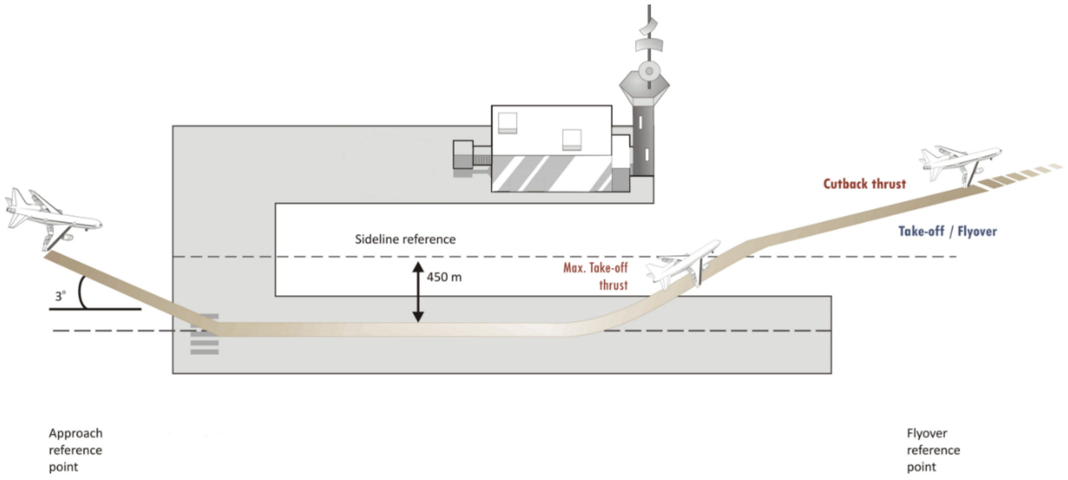


Figure 3 Aircraft Noise Measurement Points (ICAO, n.d.-c)

ICAO (n.d.-a) takes a balanced approach in managing noise produced by aircraft, which incorporates noise abatement procedures, land-use planning, operating restrictions, and reduction of noise at the source. Among these, noise abatement procedures and operating restrictions are of special importance to airlines, which also hold an economic aspect, since noncompliance with noise abatement procedures leads to fines for airlines, and operating certain types of aircraft that are relatively noisy are restricted in some airports (Law Library of Congress, 2020). Reduction of noise at source is provided with advancements in engine technologies and certain other improvements such as acoustic liners, flaps and slats designs, and the chevrons that can be found in Boeing 787 engines (NASA, 2010).

In this study, the differences between the maximum permitted noise levels at the three noise certification measurement locations and the noise level recordings at these locations are summed to reach a cumulative margin, which has the unit effective perceived noise in decibels (EPNdB). In other words, the greater the cumulative margin of an aircraft, the quieter its effective perceived noise level is. After obtaining aircraft specific noise data, noise levels of alternatives were compared with each other. Alternative noise levels were shown as multiples of the quietest aircraft, which was chosen as the datum. As it has a major impact on the environment and is regarded by the aviation industry as a subject of importance, noise levels of aircraft are considered in this study as a criterion.

3.6.4. Passenger Comfort

An important deciding factor for a passenger when choosing a flight is comfort. Essential constituents of passenger comfort in an aircraft are seat pitch and width, the size of the cabin in general and the size of overhead bins. Other than these, as it is directly related to oxygen saturations of passengers (Muhm et al., 2007), cabin altitude may be regarded as an important criterion when defining comfort.

In long-range flights, the importance of comfort increases due to increased flight times and consequently the time spent in the cabin. Owing to the fact that the study involves wide-body, long-range aircraft as alternatives, passenger comfort may be regarded as a significant criterion for this study. The criterion passenger comfort is reflected in this study with two sub-criteria, which are cabin volume per seat and cabin altitude.

3.6.4.1. Cabin Volume per Seat

Since it is difficult to compare the factors discussed above across different types of aircraft and choice of cabin layouts of airlines, the factors that are related to cabin layout are gathered under one criterion to incorporate these in the decision making model. The sole criterion selected for this purpose is cabin volume per seat, as this criterion factors out seating layout choices of airlines and focuses rather on the space that is allocated for a passenger. Spacious cabins are also highlighted by aircraft manufacturers to promote the comfort levels of their aircraft (Airbus, 2021b; Boeing, n.d.-e).

Values of cabin volume are not readily found for each aircraft that is considered as an alternative in this study. Therefore, a simple method of calculation is performed to obtain an approximate value for cabin volumes of Boeing 787-8 and Boeing 787-9. This calculation basically involves the values of maximum cabin width and cabin length (front to aft door clearance) to determine the volume of a cylinder, that is the fuselage of the aircraft. Later, a correction factor of approximately 0.40 is applied to the calculated value to reach cabin volume, as this number is calculated as the average ratio of cabin volume given in specifications versus the calculated volume.

3.6.4.2. Cabin Altitude

Regulation of air pressure inside commercial aircraft cabins is a vital subject in aviation, due to the connection between air pressure and human respiration. The need to pressurize aircraft cabins stems from the fact that atmospheric pressure decreases with increasing altitude, and despite the contents of the air staying roughly the same throughout the range of altitudes that most commercial flights take place, the reduction in air pressure also results in the decrease of partial pressure of oxygen (to about half of it at 18,000 ft, compared to sea level). The value of the partial pressure of oxygen is crucial for respiration, as it needs to be sufficient to force oxygen into blood and avoid hypoxia, a condition of oxygen deprivation (FAA, n.d.-b).

Other than hypoxia, absence of cabin pressurization is known to lead to several other conditions such as altitude sickness, decompression sickness, and barotrauma (European Union Aviation Safety Agency [EASA], 2009). To prevent the unfavorable physiological effects of high altitude flying on crew and passengers, transport category aircraft need to be pressurized. Commercial aircraft generally fly at altitudes above 30,000 ft (~10 km) while the cabins are pressurized to a certain level. The altitude that corresponds to the pressure level in the cabin is described as the cabin altitude.

According to Airworthiness Standards: Transport Category Airplanes (1964) and EASA (2020), the maximum permissible cabin altitude for a transport category aircraft is 8,000 ft. Although cabin pressure values corresponding to 8,000 ft ensure comfortable breathing levels, flying under reduced pressure levels are known to be linked with discomfort for passengers. Muhm et al. (2007) states that a flight that is conducted at an altitude between 7,000 to 8,000 ft causes discomfort after 3 to 9 hours of flight. A study conducted in a simulated setting by Oklahoma State University and Boeing resulted in passengers reporting a more comfortable flying experience, with less aches and less tiredness at 6,000 ft cabin altitude, compared to cabin pressures corresponding to 7,000 ft and 8,000 ft (Boeing, 2004). Moreover, lower cabin altitudes provided by Boeing 787 and Airbus A350 are known to reduce jet lag effects for passengers on long flights (Hepher, 2019).

The minimum cabin altitude of an aircraft in normal cruising levels is limited by the differential pressure of the aircraft, which is the difference between the cabin pressure and the atmospheric pressure. The amount of differential pressure an aircraft can endure without experiencing damage is related to the strength of the materials that the aircraft fuselage is built with. While conventional aircraft were limited in this respect due to the usage of aluminum alloys for fuselages, the improvements in material technology enabled the production of newer aircraft such as Airbus A350 and Boeing 787 with more durable, composite structures (Airbus, 2017; Boeing, 2006) that enabled manufacturers to further decrease cabin altitudes.

Taking into account its relation to several aspects of passenger comfort, cabin altitude is an essential criterion in selecting a passenger aircraft which has not been considered in other aircraft selection studies before.

3.7. Alternative Aircraft

In this section, the alternatives involved in the case study are discussed briefly. Four different wide-body passenger aircraft are selected as alternatives. These are Boeing 787-8, Boeing 787-9, Airbus A330-900 and Airbus A350-900. These aircraft were introduced to airlines in the last decade and have the highest order counts among other wide-body aircraft introduced in this period. The selected aircraft differ from their predecessors with a number of advancements in certain aspects, such as improved fuel consumption rates, reduced noise levels, increased reliability, and lower cabin altitudes. The total order counts of the alternative aircraft are shown in Table 4 (Airbus, 2021e; Boeing, 2021b).

Table 4 Total Aircraft Orders

Aircraft	Orders
Boeing 787-8	417
Boeing 787-9	893
Airbus A330-900	323
Airbus A350-900	747

3.7.1. Boeing 787-8

With the introduction of Boeing 787, Boeing presented various improvements over the previous generation of wide-body aircraft. The engines developed for the Boeing 787 family enables 20% less fuel consumption and 20% less CO_2 emissions compared to previous similar aircraft (Boeing, n.d.-c). The aircraft produces less noise with chevrons on the engine cowling, ensuring a quieter environment and cabin. Also adding to the comfort of passengers is the lower cabin altitude which reduces fatigue and a spacious cabin. Boeing highlights high amounts of composite materials usage in the airframe, which reduces the weight by 20% compared to conventional aircraft. According to the company, the use of composites in the airframe reduces operating costs by reducing scheduled and nonroutine maintenance (Boeing, 2006).

The first and smallest variant of the Boeing 787 family, Boeing 787-8, had its first flight in 2009. The aircraft started service in 2011 with launch customer All Nippon Airways and its main operators include All Nippon Airways, Qatar Airways and Japan Airlines. As of November 2021, Boeing 787-8 has 417 orders and 377 deliveries (Boeing, 2021b).

3.7.2. Boeing 787-9

The second variant of the 787 family is the Boeing 787-9, which was first flown in 2013. The aircraft entered into service in 2014 with Air New Zeeland. As Boeing 787-8 and Boeing 787-9 belong to the same aircraft family, the characteristics related to technology improvements described for Boeing 787-8 section apply to Boeing 787-9 as well. Boeing 787-9 differs from its smaller variant in terms of fuselage length and MTOW, enabling it further seating and cargo capacity, and slightly increased range. Various customers placed a total of 893 Boeing 787-9 orders, of which 568 has been delivered as of November 2021 (Boeing, 2021b). Boeing 787-9 is operated by a vast number of airlines, including Air Canada, Etihad Airways, Lufthansa, and Turkish Airlines.

3.7.3. Airbus A330-900

Developed from Airbus A330 and initially named Airbus A330neo for new engine option, Airbus A330-900 had its first flight in 2017 and entered service with TAP Air

Portugal in 2018. Airbus redesigned the wings of the aircraft and increased the wingspan, and together with the new engines and aerodynamic features such as composite winglets, the aircraft achieves 25% reductions in fuel consumption and CO_2 emissions in comparison to previous generation. These improvements and increased composite materials usage enabled Airbus to add 10 additional seats and enhance the range capabilities of Airbus A330 from 6350 nm to 7200 nm for the longer variant of the family (Airbus, 2021a). Airbus A330-900 has 323 orders and 63 were delivered as of September 2021 (Airbus, 2021e).

3.7.4. Airbus A350-900

Airbus A350-900 completed its first flight in 2013. With its typical two-class seating capacity of 315 passengers, Airbus A350-900 is a competitor to variants of Boeing 787 and Boeing 777 families. Airbus achieved similar advantages like Boeing 787 when designing the aircraft. With the engines developed by Rolls-Royce and weight reduction thanks to advanced materials usage, Airbus A350-900 reduces fuel burn by 25% compared to Boeing 777-200ER, a previous generation aircraft (Airbus, 2021c). The aircraft also benefits from the technology of the engines in terms of reduced noise levels. In addition to reduced fuel consumption values, Airbus states that using advanced materials such as titanium and carbon-fiber prevents corrosion and fatigue, which in turn lowers maintenance costs. Airbus also promotes passenger comfort, emphasizing a smooth ride, clean air, and spaciousness of Airbus A350-900. As of September 2021, the company has 747 orders on Airbus A350-900 and delivered 386 of these (Airbus, 2021e). Major operators include Singapore Airlines, Qatar Airways, and Cathay Pacific.

3.8. Data Collection

To determine the weights of criteria and to discover the interactions among these, questionnaires prepared for AHP and DEMATEL methods were applied to four airline industry experts/DMs with more than 10 years’ experience in the industry each. The experts have experience in various fields of airline industry, such as fleet planning and aircraft acquisitions, and air transportation economics. In the following sections, the data collected for this study is presented. First, the PCMs constructed through expert judgments for the AHP method are shown. Then, the DRM constructed for the

DEMATEL method is presented. Finally, data belonging to the alternative aircraft that forms the decision matrix of the TOPSIS method is presented. Approval of the METU Human Subjects Ethics Committee is provided in Appendix A.

3.8.1. PCMs – AHP Method

Through questionnaires, individual judgments of four aviation experts were gathered to construct PCMs for the main and sub-criteria levels. The fundamental scale, a nine-point scale suggested by Saaty (1990) and presented in Section 3.1. was used in the questionnaire. Before aggregating the individual judgments of experts, consistencies of PCMs are checked. As discussed previously in Section 3.1, tolerable values of CR should be below 0.20. Among the four experts who participated in the questionnaires, judgments of three experts are found to be consistent enough to be included in the study.

To aggregate the individual preferences of the experts, geometric mean method is used. Aczél and Saaty (1983), and Saaty (2008), propose the use of the geometric mean method as it conserves the reciprocal structure of the PCM while aggregating the preferences of the individuals. When the geometric mean method is used to combine individual preferences, CR value of the aggregated matrix can be calculated in the same manner as if the matrix was filled according to individual judgments (Saaty, 1989). The geometric mean method is also used in Goossens and Basten (2015) as well as Kiracı and Bakır (2018a).

The PCM obtained for the main criteria level by the geometric mean method is provided in Table 5. The CR of the aggregated PCM is calculated as 0.036, which is below the requirement suggested by Saaty for a PCM to be considered as consistent.

Table 5 Aggregated PCM of Main Criteria

	Economics	**Technical Characteristics**	**Environmental Impact**	**Passenger Comfort**
Economics	1	1.32	4.40	4.21
Technical Characteristics	0.76	1	4.79	4.79
Environmental Impact	0.23	0.21	1	2.14
Passenger Comfort	0.24	0.21	0.47	1

For the sub-criteria level, PCMs are constructed by combining individual judgments through the geometric mean method as well. Table 6 demonstrates the aggregated PCM of technical characteristics sub-criteria. As the CR of this PCM equals 0.020, the combined matrix has acceptable consistency.

Table 6 Aggregated PCM of Technical Characteristics Sub-criteria

	Range	**Seat Capacity**	**Cargo Capacity**	**Reliability**
Range	1	0.62	2.24	0.27
Seat Capacity	1.63	1	2.06	0.24
Cargo Capacity	0.45	0.38	1	0.16
Reliability	3.71	4.21	6.30	1

As the sub-criteria number under the main criteria economics, environmental impact, and passenger comfort equal to two, these PCMs have perfect consistency regardless of the strength of preference. These PCMs are presented in Appendix B.

3.8.2. DRM - DEMATEL Method

For the application of the DEMATEL method, the same experts were asked to elicit their judgments through a questionnaire. A five-point scale from 0 to 4 was used to indicate the level of direct influence of one criterion on another. To aggregate three individual judgments, arithmetic mean method is used. In the literature, arithmetic mean method is used by Sara et al. (2015), Wang et al. (2012), and Wu (2008). The aggregated DRM is provided in Table 7.

Table 7 DRM

	PR	**DOC**	**RA**	**SC**	**CC**	**RE**	**CO_2**	**NL**	**CV**	**CA**
PR	0.00	3.00	2.67	3.00	2.33	2.00	2.33	2.33	1.33	0.00
DOC	3.33	0.00	3.33	3.33	2.67	2.67	3.00	2.00	1.33	0.00
RA	2.67	3.00	0.00	2.67	3.00	1.00	1.67	1.33	1.33	0.33
SC	2.67	2.67	2.67	0.00	2.33	1.00	1.67	1.33	2.33	0.00
CC	2.00	2.33	2.67	2.33	0.00	1.00	1.33	1.33	1.00	0.00
RE	2.67	3.00	2.00	1.33	2.00	0.00	1.67	1.33	0.33	0.00
CO_2	3.00	3.00	2.33	2.00	2.00	0.67	0.00	0.67	0.67	0.00
NL	1.67	1.00	1.33	1.00	1.67	0.67	0.67	0.00	0.33	0.00
CV	2.00	1.67	2.00	2.67	2.00	0.33	0.67	0.67	0.00	0.00
CA	0.67	0.67	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00

PR = Price. DOC = Direct Operating Cost. RA = Range. SC = Seat Capacity. CC = Cargo Capacity. RE = Reliability. CO_2 = CO_2 Emissions. NL = Noise Level. CV = Cabin Volume per Seat. CA = Cabin Altitude.

3.8.3. Aircraft Data

For the implementation of TOPSIS method, aircraft data regarding each criterion are either gathered through various sources or calculated using certain aircraft data. Aircraft prices are acquired through the list prices published by the aircraft manufacturers. DOC values of aircraft are calculated based on the AEA method, which is explained in detail in Section 3.6.1.2. Data regarding range, seat capacity and cargo capacity are readily available on the manufacturers' websites and are obtained from related webpages. As previously discussed in Section 3.6.2.4, reliability criterion is quantified with the ETOPS rating of aircraft, for which the data are available on type certificate data sheets of aircraft. CO_2 emissions data are derived from fuel consumption values of the aircraft by multiplying fuel consumption values by 3.15, which is a constant determined by the chemical reaction of kerosene combustion. To determine fuel consumption values of aircraft, an Excel file provided by Burzlaff (2017) is used with input data from manufacturers' documents. The fuel consumption calculations are based on a flight distance of 4,345 nm with maximum number of passengers. Noise level data are acquired from an international aircraft noise database, NoisedB, which was developed by ICAO and French General Directorate of Civil Aviation. Cabin volume per seat data are obtained from aircraft characteristics documents for Airbus alternatives, and are calculated for Boeing alternatives with available aircraft data, as mentioned in Section 3.6.4.1. Cabin altitude data for Boeing alternatives and Airbus A350-900 are gathered from manufacturers' websites, whereas for Airbus A330-900 an assumption is made based on a news article by Hepher (2019). The data sources were exhibited in detail in Table 8.

Table 8 Data Sources

Criteria	**Sources**
Price	Airbus (2018), Boeing (n.d.)
DOC	AEA (1987), Airbus (2020a), Airbus (2020b), Boeing (2018), GE Aviation (n.d.), IATA (2021b), Rolls-Royce (2016), Rolls-Royce (2018), U.S. Bureau of Labor Statistics (2021), Vasconcelos Oliveira (2015)
Range	Airbus (n.d.-a), Airbus (n.d.-b), Boeing (n.d.-b)
Seat Capacity	Airbus (2020a), Airbus (2020b), Boeing (n.d.-b)
Cargo Capacity	Airbus (2020a), Airbus (2020b), Boeing (2018)
Reliability	Airbus (2019), Boeing (2014), EASA (2014)
CO_2 Emissions	Airbus (2020a), Airbus (2020b), Boeing (2018), Burzlaff (2017)
Noise Level	ICAO (n.d.-d), ICAO (n.d.-e), ICAO (2018), ICAO (2019)
Cabin Volume per Seat	Airbus (2020a), Airbus (2020b), Boeing (2018)
Cabin Altitude	Airbus (n.d.-b), Boeing (n.d.-d), Hepher (2019)

The performance values of alternatives that form the decision matrix of the TOPSIS method are presented in Table 9.

Table 9 Performance Values of Alternative Aircraft

Alternatives	Criteria									
	Price ($M)	DOC ($/block hour)	Range (NM)	Seat Capacity	Cargo Capacity (# of LD3 containers)	Reliability (ETOPS rating in min.)	CO_2 Emissions (kg/100 km per pax)	Noise Level (multiple of the quietest a/c)	Cabin Volume per Seat (m^3/seat)	Cabin Altitude (ft)
787-8	248.3	13,365	7305	242	28	330	7.91	1.10	1.46	6,000
787-9	292.5	15,363	7530	290	36	330	7.37	1.53	1.41	6,000
A330-900	296.4	15,952	7200	310	33	285	8.10	2.72	1.20	7,500
A350-900	317.4	16,497	8100	315	36	370	7.34	1.00	1.50	6,000

CHAPTER 4

RESULTS AND DISCUSSIONS

In this chapter, results of the two approaches proposed for selection of the best wide-body passenger aircraft are presented. First, results obtained with the AHP method are shown. Later, results of the DEMATEL method are presented. Finally, results of AHP-TOPSIS and DEMATEL-TOPSIS approaches are provided and compared.

4.1. Results of the AHP Method

In Section 3.8.1, the data collected for the application of AHP method were presented. In order to derive criteria weights from the judgments of experts, column elements of combined PCMs are normalized and their arithmetic average are taken as discussed in Section 3.1. The normalized PCMs are provided in Appendix C. The derived weights of main criteria and local weights of sub-criteria are provided in Figure 4. The local weights of sub-criteria show the importance level of each sub-criterion under its respective main criterion.

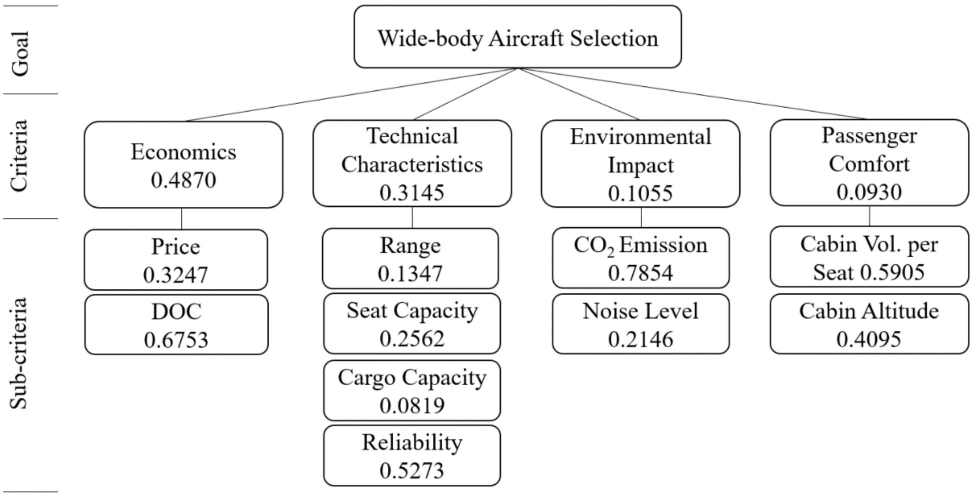


Figure 4 Weights of Main Criteria and Local Weights of Sub-criteria

Looking at the weights of main criteria, it is seen that economics and technical characteristics criteria have much more significance when selecting an aircraft compared to environmental impact and passenger comfort criteria, with a combined weight of 0.8015. Predictably, economics criterion has the highest weight among others with a weight of 0.4870, as an aircraft's price and operating costs have significant impact on an airline's profitability and financial position. Reflecting the operational capabilities of an aircraft, technical characteristics criterion is ranked second among other main criteria. The importance placed on technical characteristics is reasonable considering the criterion's overall effect on serviceability and flexibility of an airline. On the other hand, it is found that environmental impact and passenger comfort criteria have less importance, having relatively close weights with 0.1055 and 0.0930, respectively. This shows that priorities of stakeholders other than the airlines are not entirely taken into consideration when selecting a passenger aircraft. The significance of environmental impact criterion may be subject to change in the near future with industry targets on the horizon regarding the reduction of CO_2 emissions and noise levels.

The global weights of sub-criteria, which have a decisive influence on the results of the AHP-TOPSIS approach are presented in Table 10. These weights were obtained by multiplying the local weight of each sub-criterion with its respective main criterion weight.

Table 10 Global Weights of Sub-criteria – AHP Method

Sub-criteria	w_i
Price	0.1581
DOC	0.3289
Range	0.0424
Seat Capacity	0.0806
Cargo Capacity	0.0258
Reliability	0.1658
CO_2 Emission	0.0829
Noise Level	0.0226

Table 10 (continued)

Cabin Vol. per Seat	0.0549
Cabin Altitude	0.0381

As demonstrated in Table 10, DOC is seen as the most important criterion having a weight of 0.3289. As discussed in detail in Section 3.6.1.2, DOC covers major cost items such as financial cost, crew cost, charges and fees, maintenance cost and fuel cost. In this regard, the high amount of weight acquired by DOC is justified, since it is essentially a combination of several criteria merged into one. The importance attributed to DOC can be further validated, considering it constitutes approximately 50% of the total operating expenses of airlines (Belobaba et al., 2016). Reliability is ranked second in AHP results, with a weight equaling 0.1658. This result is also expected since reliability is a crucial aspect for conducting a safe and efficient flight. Being closely associated to the operational availability of an aircraft, reliability is also related to an aircraft's revenue generating capabilities, which further contributes to the criterion's importance. In line with expectations, price is found to be among the top priorities of aviation experts when selecting an aircraft. It is ranked third with a weight of 0.1581. Rank four is acquired by CO_2 emission criterion, weight of which is 0.0829. CO_2 emission has much more importance compared to noise pollution, which is seen as the least important criterion. This finding may be attributed to the role of CO_2 emissions in climate change, which is an issue regarded as having a greater urgency compared to noise pollution. When passenger comfort criteria are taken into account, cabin volume per seat criterion has more weight compared to cabin altitude, as cabin spaciousness might be more salient compared to cabin altitude at first glance.

Examining the results, the importance attributed to range is lower than expected. Range of an aircraft is one of the factors that play a role in determining destinations that can be served and it may be regarded as a strategic factor. However, like most of the criteria in this setting, the weight of range criterion may be subject to change from one airline to another. Considering this is a hypothetical study that is not specific to a certain airline, the weight attributed to range may be regarded as understandable. Another low weighted criterion that is observed in AHP results is cargo capacity. As discussed previously, about half of total air cargo is carried in a passenger aircraft (IATA, 2020) and air cargo market is expected to grow by an average annual growth rate of 4% in the 2021-2040 period (Boeing, 2021a). Despite the potential of air cargo market expansion, Boeing (2020) reports that not all passenger aircraft destinations have high cargo demand and schedules may not coincide with shipping timings. Along with limitations on cargo carried in the lower deck of a passenger aircraft due to safety regulations and size constraints, carrying cargo on a passenger aircraft may be suboptimal, which justifies the weight attributed to cargo capacity criterion.

When the results of the AHP method are compared with those of other aircraft selection studies that use AHP (Dozic & Kalic, 2014; Kiracı & Bakır, 2018a) and fuzzy AHP (Ahmed et al., 2020; Bruno et al., 2015; Kiracı & Akan, 2020) methods for weight determination, it is observed that the weight attributed to economics related criteria such as price and operating costs are also high compared to other criteria used in those studies. Although the importance attributed to environmental impact criterion is ranked second in Ahmed et al. (2020), the weights of environmental impact criteria are relatively low in several studies (Bruno et al., 2015; Kiracı & Akan, 2020), in line with our findings.

4.2. Results of the DEMATEL Method

In order to discover criteria interactions and obtain weights, data gathered to construct DRM of the DEMATEL method is used. Following the steps described in Section 3.2, the DRM is normalized (see Appendix D), then TRM is obtained using the normalized DRM. The TRM is provided in Table 11.

Table 11 TRM

	PR	**DOC**	**RA**	**SC**	**CC**	**RE**	**CO_2**	**NL**	**CV**	**CA**
PR	0.340	**0.460**	**0.441**	**0.444**	**0.409**	0.263	0.338	0.300	0.224	0.007
DOC	**0.520**	0.385	**0.509**	**0.498**	**0.463**	0.312	**0.395**	0.313	0.245	0.008
RA	**0.419**	**0.430**	0.304	**0.406**	**0.408**	0.209	0.291	0.244	0.211	0.020

Table 11 (continued)

SC	**0.414**	**0.412**	**0.408**	0.292	0.378	0.205	0.286	0.239	0.248	0.006
CC	0.347	0.358	0.366	0.347	0.242	0.183	0.244	0.215	0.174	0.006
RE	0.383	**0.394**	0.350	0.317	0.334	0.147	0.267	0.223	0.148	0.005
CO_2	**0.401**	**0.400**	0.370	0.351	0.340	0.181	0.200	0.199	0.168	0.006
NL	0.228	0.201	0.211	0.194	0.216	0.114	0.142	0.096	0.093	0.003
CV	0.311	0.297	0.307	0.330	0.294	0.136	0.192	0.167	0.116	0.005
CA	0.112	0.112	0.125	0.123	0.120	0.045	0.060	0.051	0.044	0.002

In order to filter out weak interactions between criteria, a threshold value is used. The threshold value is the arithmetic average of the elements of the TRM, and is calculated as 0.248. To further differentiate the strength of interactions, the half of the difference between the highest value of the TRM (0.520) and the threshold value is used to determine a value which equals 0.384. In the TRM, values greater than 0.384 are shown bold, values between 0.248 and 0.384 are shown black, and values lower than the threshold value are shown with gray.

To determine criteria weights and construct IRMs of criteria, sums of rows (D) and columns (R) of the TRM are calculated. The weight of each criterion is calculated in accordance with step 6 in Section 3.2, and is presented in Table 12. As discussed in Section 3.2, $(D + R)$ values form the horizontal axis, and $(D - R)$ values form the vertical axis of the IRM.

Table 12 Weights of Sub-criteria – DEMATEL Method

Sub-criteria	$\boldsymbol{w_i}$
Price	0.1337
DOC	0.1416
Range	0.1267

Table 12 (continued)

Seat Capacity	0.1238
Cargo Capacity	0.1143
Reliability	0.0884
CO_2 Emission	0.1005
Noise Level	0.0715
Cabin Vol. per Seat	0.0769
Cabin Altitude	0.0225

In the IRMs, interactions that have values greater than 0.384 are depicted with thick arrows for high influences, while interactions between 0.248 and 0.384 are depicted with thin arrows for moderate influences. Figures 5-7 illustrate the IRMs of criteria. IRMs of criteria that have the most interactions, which are price and DOC, were separately shown.

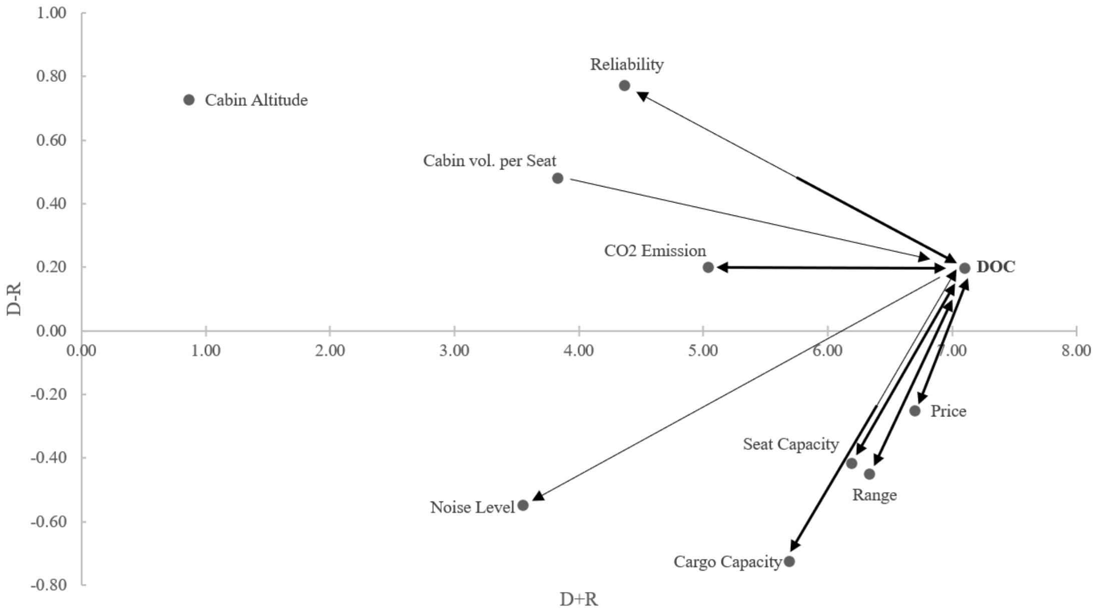


Figure 5 IRM of DOC

Along with price, DOC has the most interactions compared to any other criteria and the highest five values of the TRM belong to this criterion. On account of having the highest valued influences, DOC attains a weight of 0.1416 and it is ranked first in the DEMATEL model as well. As expected, DOC is closely associated with price. This interaction may be regarded as a direct effect, since the two criteria also have a very high positive correlation with a correlation coefficient of 0.9891. Examining Figure 5, it is found that MTOW related criteria such as range, seat capacity, and cargo capacity are connected to DOC, and certain changes in these criteria may affect each other. This finding is not surprising, since DOC items are mainly related to the size of the aircraft. The IRM also demonstrates that DOC has a two-way interaction with reliability. This can be explained by the fact that reliability is strongly associated with maintenance. Further, it is seen that DOC has a strong interaction with CO_2 emission, which may be interpreted as an indirect effect that originates from the connection between DOC and fuel consumption.

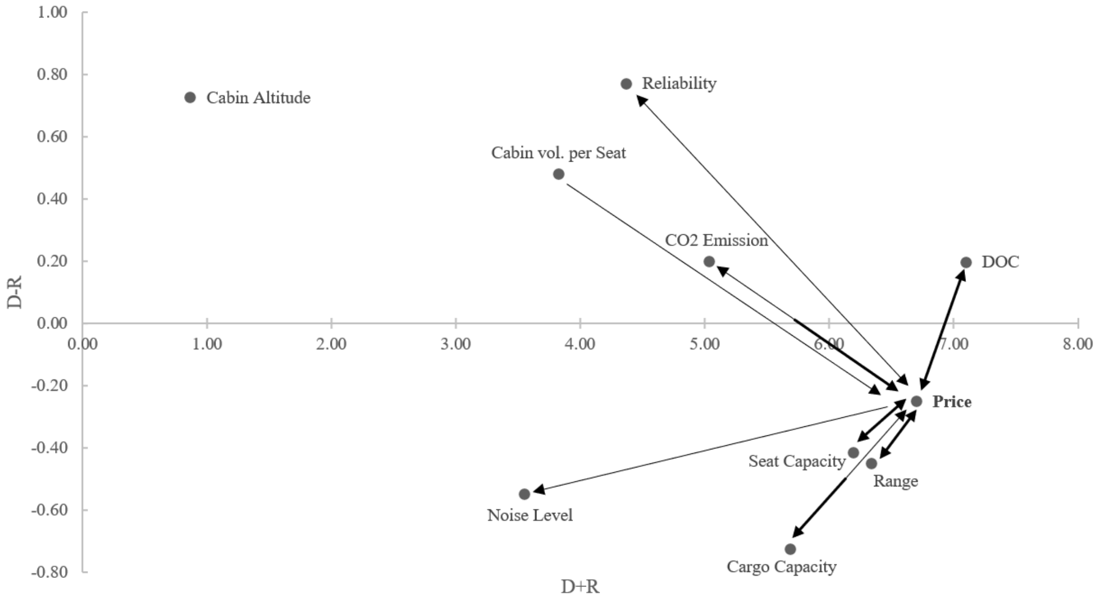


Figure 6 IRM of Price

Price has the second highest prominence value with a $(D + R)$ value of 6.6978. The criterion is in the effect group as its $(D - R)$ value is negative, meaning that this criterion is influenced more than it gives influence on other criteria. Price has strong interactions with DOC, range and seat capacity. The strength of the relation between price and seat capacity can be further validated with their positive correlation coefficient equaling 0.9689. In addition, price is moderately influenced by cargo capacity and cabin volume per seat criteria. These findings are an indication of the effect of technical characteristics criteria on the acquisition price of an aircraft, which is expected. It is also observed that CO_2 emission criterion has a high influence on price, which may be an indirect effect of the development costs of aircraft engines that provide improved fuel consumption values. On the other hand, price has a moderate interaction with reliability and is influenced more than it influences reliability. It is evident that an aircraft that has less issues related to its airframe, systems and engines would have a higher price, which explains the interaction of reliability and price. Figure 6 also shows the influence of price on environmental impact criteria. As research and development costs are a part of the price of the aircraft, these influences may be attributed to this indirect effect.

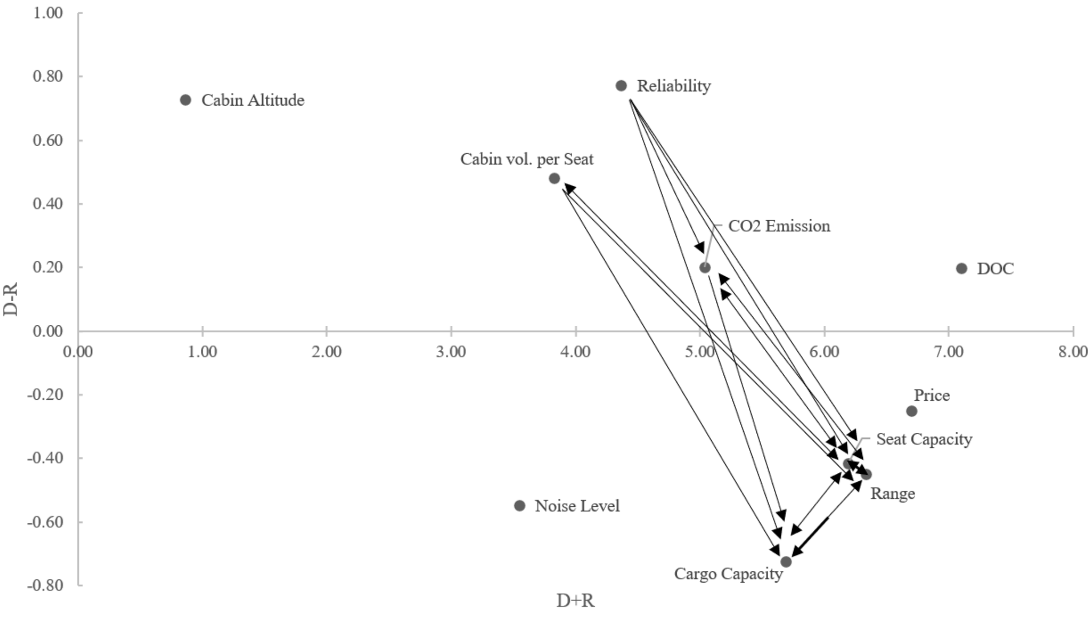


Figure 7 IRM (excluding the interactions of DOC and price)

As shown in Figure 7, range is the criterion with the third highest $(D + R)$ value, making it the third most important criterion with a weight of 0.1267. The IRM reveals that range has notable interactions with seat capacity and cargo capacity. This is reasonable, considering that payload and range have a tradeoff relationship. Range also has a moderate interaction with cabin volume per seat criterion, which may be due to an indirect effect resulting from the cabin volume and size relation. Further, range and CO_2 emission receive moderate influences from each other, as fuel consumption values differ greatly with the length of travel.

Aside from its strong interactions with DOC, price, and range, seat capacity is seen to have moderate level of interactions with cargo capacity, CO_2 emission, and cabin volume per seat. As both seat capacity and cargo capacity are constituents of payload, the interaction between these criteria are justified. Seat capacity and cargo capacity are ranked fourth and fifth in terms of weight, respectively. Figure 7 also shows that cargo capacity has dependency relationships with the same criteria as seat capacity, and is influenced by the same criteria as seat capacity. However, it is not as influential as seat capacity, thus has a lower $(D - R)$ value. Both seat capacity and cargo capacity have relations with CO_2 emission criterion. This finding is reasonable as the weight of the aircraft is one of the factors that determines the fuel consumption rate. Further, the IRM depicts that cabin volume per seat is notably influenced by seat capacity only. Based on their (D) and (R) values, CO_2 emission and cabin volume per seat criteria have weights 0.1005 and 0.0769, respectively, which situate them two places lower in rank compared to the AHP model.

It is observed from Figure 7 that reliability holds the highest $(D - R)$ value, indicating that this criterion gives more influence than it receives, which can also be seen from the number of unidirectional arrows originating from reliability criterion. In accordance with the threshold values described, reliability has a high influence on DOC, and moderate influence on price, range, seat capacity, cargo capacity and CO_2 emission criteria. The findings highlight that reliability has a noteworthy connection with the capacity and capabilities of an aircraft. Therefore, it can be suggested that fleet planners should take into consideration the impact of reliability on aircraft capacity when selecting aircraft. Aircraft with low levels of reliability may be subject to grounding more frequently, which would mean reduced capacity and lost revenue for an airline. The impact of reliability on DOC is more apparent, since reliability can be sustained through maintenance, and maintenance cost is a DOC item. Contrary to its high influence on other criteria, reliability is seventh in terms of its $(D + R)$ value and has a weight that equals 0.0884, which is approximately half of the weight it attained in the AHP model.

Cabin altitude was observed to have no notable effect on any of the criteria in the model. The criterion's importance is affected by its low level of impact, making it the least important criterion in the DEMATEL method with a weight of 0.0225.

It must be noted that some interactions between criteria may not be readily explainable as matrix T not only includes the direct influences, but also the indirect influences. Nevertheless, the IRMs provide valuable indications regarding the interdependencies among criteria.

4.3. Results of AHP-TOPSIS and DEMATEL-TOPSIS Approaches

The final step of this study is the determination of the best wide-body aircraft. This is achieved through the TOPSIS method with the two sets of criteria weights obtained in the previous sections.

As the application of the TOPSIS method requires, a decision matrix that has the performance values of alternatives (Table 9) as its elements is formed. This matrix is normalized according to step 2 of Section 3.3 and is provided in Appendix E. Using the criteria weights derived with the AHP method, the weighted normalized decision matrix of the AHP-TOPSIS approach is formed as in Table 13.

Table 13 Weighted Normalized Decision Matrix: AHP-TOPSIS

	PR	**DOC**	**RA**	**SC**	**CC**	**RE**	**CO_2**	**NL**	**CV**	**CA**
787-8	0.068	0.143	0.021	0.034	0.011	0.083	0.043	0.007	0.029	0.018
787-9	0.080	0.165	0.021	0.040	0.014	0.083	0.040	0.010	0.028	0.018
A330-900	0.081	0.171	0.020	0.043	0.013	0.072	0.044	0.018	0.024	0.022
A350-900	0.087	0.177	0.023	0.044	0.014	0.093	0.040	0.007	0.030	0.018

For the calculation of the positive and negative ideal solutions, the criteria are categorized. While range, seat capacity, cargo capacity, reliability and cabin volume per seat are the benefit criteria, price, DOC, CO_2 emissions, noise level and cabin altitude are the cost criteria. The maximum value for each benefit criterion and the minimum value for each cost criterion are identified from the weighted normalized decision matrix. The positive and negative ideal solutions for the AHP-TOPSIS approach are exhibited in Table 14.

Table 14 Positive and Negative Ideal Solutions: AHP-TOPSIS

	PR	**DOC**	**RA**	**SC**	**CC**	**RE**	**CO_2**	**NL**	**CV**	**CA**
A^+	0.068	0.143	0.023	0.044	0.014	0.093	0.040	0.007	0.030	0.018
A^-	0.087	0.177	0.020	0.034	0.011	0.072	0.044	0.018	0.024	0.022

To measure the relative closeness of alternatives to the ideal solution, the respective distance of each alternative from the positive and negative ideal solutions are calculated. Table 15 provides the distances, the relative closeness values and the final ranking of each alternative aircraft obtained with the AHP-TOPSIS approach.

Table 15 Distances to Ideal Solutions, Relative Closeness Values and Rankings: AHP-TOPSIS

	S_i^+	S_i^-	C_i	**Ranking**
787-8	0.0151	0.0421	0.7357	1
787-9	0.0271	0.0221	0.4495	2
A330-900	0.0401	0.0126	0.2397	4
A350-900	0.0385	0.0278	0.4194	3

Table 15 reveals that Boeing 787-8 is the best performing aircraft as it is closest to the ideal solution based on the results of the AHP-TOPSIS approach in this study. Despite providing smaller capacity for airlines compared to the other alternatives of the study, Boeing 787-8 has a lower list price and DOC. The relatively high weight attributed to price and DOC in the AHP model makes Boeing 787-8 the alternative closest to the ideal solution. The results also show that, Boeing 787-9 and Airbus A350-900 are ranked second and third, respectively, and Airbus A330-900 is the worst performing alternative and is ranked fourth.

The weighted normalized decision matrix, and the positive and negative ideal solutions of the DEMATEL-TOPSIS approach are provided in Tables 16-17. Table 18 presents the DEMATEL-TOPSIS results.

Table 16 Weighted Normalized Decision Matrix: DEMATEL-TOPSIS

	PR	**DOC**	**RA**	**SC**	**CC**	**RE**	**CO_2**	**NL**	**CV**	**CA**
787-8	0.057	0.062	0.061	0.052	0.048	0.044	0.052	0.023	0.040	0.011
787-9	0.067	0.071	0.063	0.062	0.062	0.044	0.048	0.032	0.039	0.011
A330-900	0.068	0.074	0.060	0.066	0.056	0.038	0.053	0.056	0.033	0.013
A350-900	0.073	0.076	0.068	0.067	0.062	0.050	0.048	0.021	0.041	0.011

Table 17 Positive and Negative Ideal Solutions: DEMATEL-TOPSIS

	PR	**DOC**	**RA**	**SC**	**CC**	**RE**	**CO_2**	**NL**	**CV**	**CA**
A^+	0.057	0.062	0.068	0.067	0.062	0.050	0.048	0.021	0.041	0.011
A^-	0.073	0.076	0.060	0.052	0.048	0.038	0.053	0.056	0.033	0.013

Table 18 Distances to Ideal Solutions, Relative Closeness Values and Rankings: DEMATEL-TOPSIS

	S_i^+	S_i^-	C_i	**Ranking**
787-8	0.0228	0.0411	0.6429	2
787-9	0.0199	0.0327	0.6216	3
A330-900	0.0430	0.0177	0.2912	4
A350-900	0.0215	0.0446	0.6744	1

When the results of the DEMATEL-TOPSIS approach presented in Table 18 are examined, it is seen that the ranking of the alternatives other than Airbus A330-900 are changed. The approach results in close C_i values except for Airbus A330-900. Among the four alternatives, the closest aircraft to the ideal solution is Airbus A350-900. The wide-body aircraft is the alternative with the best performance values in eight criteria, which justifies its ranking.

The findings indicate that Airbus A330-900 is the alternative with the lowest relative closeness value in both methods, which is consistent with the number of orders it has acquired over the years. Compared to the other alternatives considered in this study, Airbus A330-900 has the lowest number of orders with 323 orders as of September 2021 (Airbus, 2021e).

CHAPTER 5

CONCLUSIONS

As the main source of revenue, aircraft play a vital role in the operations of airline companies. The decision regarding the type of aircraft to operate have effects on the operational efficiency and flexibility, and financial status of an airline. The selection process of an aircraft involves various criteria and may be regarded as a complex problem that can be solved by MCDM methods. This study investigates wide-body passenger aircraft selection problem utilizing different MCDM methods, which are AHP, DEMATEL, and TOPSIS. The interactions of the criteria involved in the decision making problem are also explored via DEMATEL method.

In this study, criteria specific to the selection of a wide-body aircraft are investigated through a literature review and are determined with the addition of a new criterion. A total of ten criteria are introduced, which enables to investigate the decision problem using as much constituents as possible to represent the whole setting. A widely known MCDM method, AHP, is applied initially to construct a decision hierarchy to break down the decision problem into levels. This way, the criteria are grouped under their respective parent category. AHP is used to determine weights of criteria in the first approach of the study, which is the AHP-TOPSIS approach. In order to detect the effect of dependency relations between criteria on the results, weights determined with the DEMATEL method are used in the second approach of the study, which is the DEMATEL-TOPSIS approach. Further, DEMATEL method is used to discover the direct and indirect influences that criteria have on each other, and to construct IRMs which show the level and direction of these influences.

In the latter sections, descriptions of the criteria are presented. The decision problem is structured in a way to incorporate four different aspects of a wide-body passenger aircraft, which are economics, technical characteristics, environmental impact, and passenger comfort criteria. It is proposed in this study that, a technical characteristics sub-criterion, reliability, is measured with the ETOPS rating of an aircraft, as it is associated with reliability. Further, a new criterion to help assess passenger comfort is introduced, which is cabin altitude. Brief descriptions of the four alternative aircraft selected based on global sales performance values are presented as well. Finally, data acquired through questionnaires for AHP and DEMATEL method applications, and quantitative aircraft data are provided.

The results and discussions present the weights determined for the criteria, IRMs of criteria, and the results of the two approaches proposed for the decision problem. Based on the weights determined, it is found that the rank of DOC criterion is consistent, having attained the first rank in both methods. Price is ranked relatively high in both methods, having acquired the weights 0.1337 and 0.1581 in AHP and DEMATEL methods, respectively. Considering that aircraft manufacturers are known to provide airlines with discounted prices when buying aircraft, the amount of discount a manufacturer offers may hold a decisive impact on the final decision on the type of aircraft to purchase. The significance attributed to price, seat capacity and noise level are also found to be fairly consistent across the methods based on a comparison of their ranks, as they moved only one position in the rankings.

Using the TRM of the DEMATEL method, interactions between criteria are discovered. It is detected that DOC and price had the most notable interactions with other criteria, which coincides with the relatively high weights attained by these criteria. Reliability is calculated to be the most influential criterion, and the findings indicate that it has high influence on DOC. The criterion is also found to have influence on aircraft capacity related criteria, indicating that high reliability is essential to avoid lost revenue due to reduced capacity.

The findings indicate that the top three rankings reached through the TOPSIS method across the two approaches change, and that each approach deliver a different alternative as the best option, which are Boeing 787-8 for the AHP-TOPSIS approach, and Airbus A350-900 for the DEMATEL-TOPSIS approach. Despite this difference in the results, there is an agreement between both approaches on the rank of Airbus A330-900, which is determined as the worst option. The discrepancy in the outcomes of the two approaches may be attributed to the criteria dependency issue, since the AHP method requires the assumption of criteria independency, while the DEMATEL method does not.

Although certain political factors are known to play a role in the final decision on the choice of manufacturer of the aircraft, examining the order counts of the aircraft and the relative closeness values, it may be stated that the DEMATEL-TOPSIS approach provides a better approximation of real-life data compared to the AHP-TOPSIS approach.

It can be noted that, while the study at hand focused on the aircraft selection problem from an airline perspective, the findings regarding the interactions among criteria and the importance attributed to criteria may also provide insight for manufacturers in designing future aircraft that better fit the requirements of airlines. In addition, the approaches used in the study may be used by airlines to decide on which aircraft to retire from their fleet, which could provide a leaner fleet. This could especially be crucial in times of crisis such as the COVID-19 pandemic where airlines need to decide on aircraft types to be retired.

As the study is a hypothetical one, certain criteria such as fleet commonality and delivery time are not taken into consideration, as the former is specific to an airline, and the latter is dependent upon the manufacturer’s schedule, of which the data is not available publicly. Another limitation experienced in this study was the unavailability of face-to-face interviews with the experts due to the COVID-19 pandemic. Conducting face-to-face questionnaires could improve the quality of responses and provide more informed judgments.

The approaches used in this study may be applied to the narrow-body aircraft selection problem of airlines in future studies. Furthermore, the approaches may be used for freighter, regional and military cargo aircraft selection problems as well, with certain changes in the criteria used. Also, the validity of the results of this study may be checked using other MCDM methods.

REFERENCES

Aczél, J., & Saaty, T. L. (1983). Procedures for synthesizing ratio judgements. *Journal of Mathematical Psychology*, *27*(1), 93–102. https://doi.org/10.1016/0022-2496(83)90028-7

Ahmed, S. K., Sivakumar, G., Kabir, G., & Ali, S. (2020). Regional aircraft selection integrating fuzzy analytic hierarchy process (FAHP) and efficacy method. *Journal of Production Systems & Manufacturing Science*, *1*(2), 63–86.

Airbus. (n.d.-a). *A330-900: Details.* https://aircraft.airbus.com/en/aircraft/a330/a330-900

Airbus. (n.d.-b). *A350-900: Details.* https://aircraft.airbus.com/en/aircraft/a350/a350-900

Airbus. (n.d.-c). *A350 Family: An exclusive in-flight experience.* https://www.airbus.com/en/products-services/commercial-aircraft/passenger-aircraft/a350-family

Airbus. (2017). *Composites: Airbus continues to shape the future*. https://www.airbus.com/en/newsroom/news/2017-08-composites-airbus-continues-to-shape-the-future

Airbus. (2018). *Airbus aircraft 2018 average list prices.* https://www.airbus.com/content/dam/corporate-topics/publications/backgrounders/Airbus-Commercial-Aircraft-list-prices-2018.pdf

Airbus. (2019, January 28). *EASA certifies A330neo for "beyond 180 minutes" ETOPS.* https://www.airbus.com/en/newsroom/press-releases/2019-01-easa-certifies-a330neo-for-beyond-180-minutes-etops

Airbus. (2020a). *A330 aircraft characteristics - airport and maintenance planning (ac).* https://www.airbus.com/content/dam/corporate-topics/publications/bac kgrounders/techdata/aircraft_characteristics/Airbus-Commercial-Aircraft-AC-A330.pdf

Airbus. (2020b). *A350 aircraft characteristics - airport and maintenance planning (ac).* https://www.airbus.com/content/dam/corporate-topics/publications/backgrounders/techdata/aircraft_characteristics/Airbus-Commercial-Aircraft-AC-A350-900-1000.pdf

Airbus. (2021a). *A330 family: Powering into the future*. https://www.airbus.com/sites/g/files/jlcbta136/files/2021-11/EN-Airbus-A330-Facts-and-Figures-November-2021.pdf

Airbus. (2021b). *A350: Clean sheet – Clean start.* https://www.airbus.com/sites/g/files/jlcbta136/files/2021-10/Infographic-A350-Family.pdf

Airbus. (2021c). *A350: Intelligent airframe with unparalleled aerodynamics*. https://aircraft.airbus.com/en/aircraft/a350/a350-less-weight-less-fuel-more-sustainable#airframe

Airbus. (2021d). *Airbus global market forecast 2021 – 2040*. https://www.airbus.com/sites/g/files/jlcbta136/files/2021-11/Airbus-Global-Market-Forecast-2021-2040.pdf

Airbus. (2021e). *Orders and deliveries: Commercial aircraft*. https://www.airbus.com/en/products-services/commercial-aircraft/market/orders-and-deliveries

Airworthiness Standards: Transport Category Airplanes, 14 C.F.R. § 25 (1964)

Association of European Airlines. (1987). *Long range aircraft - AEA requirements* (Report No. G(T)5655).

Belobaba, P., Odoni, A. R., & Barnhart, C. (2016). *The global airline industry* (2nd ed.). John Wiley & Sons.

Black, D. A., Black, J. A., Issarayangyun, T., & Samuels, S. E. (2007). Aircraft noise exposure and resident's stress and hypertension: A public health perspective for airport environmental management. *Journal of Air Transport*

Management, *13*(5), 264–276. https://doi.org/10.1016/j.jairtraman.2007.04.003

Boeing. (n.d.-a). *About Boeing commercial airplanes: Prices.* https://www.boeing.com/company/about-bca/#/prices

Boeing. (n.d.-b). *Boeing 787 Dreamliner: Technical specs.* https://www.boeing.com/commercial/787/#/technical-specs

Boeing. (n.d.-c). *787 Dreamliner by design: A benchmark in fuel efficiency*. https://www.boeing.com/commercial/787/by-design/#/benchmark-fuel-efficiency

Boeing. (n.d.-d). *787 Dreamliner by design: Lower cabin altitude.* https://www.boeing.com/commercial/787/by-design/#/lower-cabin-altitude

Boeing. (n.d.-e). *787 Dreamliner by design: Unrivaled passenger experience.* https://www.boeing.com/commercial/787/by-design/#/unrivaled-passenger-experience

Boeing. (1999). *ETOPS maintenance on non-ETOPS airplanes.* https://www.boeing.com/commercial/aeromagazine/aero_07/etops.html

Boeing. (2004). *Boeing 7E7 offers preferred cabin environment, study finds*. https://boeing.mediaroom.com/2004-07-19-Boeing-7E7-Offers-Preferred-Cabin-Environment-Study-Finds

Boeing. (2006). Boeing 787 from the ground up. *AERO, 2006*(4), 17-24. https://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/AERO_Q406.pdf

Boeing. (2014, May 28). *Boeing receives 330-minute ETOPS certification for 787s.* https://boeing.mediaroom.com/2014-05-28-Boeing-Receives-330-Minute-ETOPS-Certification-for-787s

Boeing. (2018). *787 airplane characteristics for airport planning.* https://www.boeing.com/resources/boeingdotcom/commercial/airports/acaps/787.pdf

Boeing. (2020). *World air cargo forecast 2020–2039*. https://www.boeing.com/resources/boeingdotcom/market/assets/downloads/2020_WACF_PDF_Download.pdf

Boeing. (2021a). *Commercial market outlook 2021–2040: Air cargo outlook.* https://www.boeing.com/commercial/market/commercial-market-outlook/

Boeing. (2021b). *Orders & deliveries*. https://www.boeing.com/commercial/?cm_re=March_2015-_-Roadblock-_-Orders+%26+Deliveries/#/orders-deliveries

Braun-Unkhoff, M., Riedel, U., & Wahl, C. (2017). About the emissions of alternative jet fuels. *CEAS Aeronautical Journal*, *8*(1), 167–180. https://doi.org/10.1007/s13272-016-0230-3

Bruno, G., Esposito, E., & Genovese, A. (2015). A model for aircraft evaluation to support strategic decisions. *Expert Systems with Applications*, *42*(13), 5580–5590. https://doi.org/10.1016/j.eswa.2015.02.054

Burzlaff, M. (2017). *Aircraft Fuel Consumption – Estimation and Visualization*. Hamburg University of Applied Sciences, Aircraft Design and Systems Group (AERO). https://doi.org/10.7910/DVN/2HMEHB

Büyüközkan, G., & Güleryüz, S. (2016). An integrated DEMATEL-ANP approach for renewable energy resources selection in Turkey. *International Journal of Production Economics*, *182*, 435–448. https://doi.org/10.1016/j.ijpe.2016.09.015

Chang, B., Chang, C.-W., & Wu, C.-H. (2011). Fuzzy DEMATEL method for developing supplier selection criteria. *Expert Systems with Applications*, *38*(3), 1850–1858. https://doi.org/10.1016/j.eswa.2010.07.114

Clark, P. (2007). *Buying the big jets: Fleet planning for airlines* (2nd ed.). Ashgate Publishing.

Dalalah, D., Hayajneh, M., & Batieha, F. (2011). A fuzzy multi-criteria decision making model for supplier selection. *Expert Systems with Applications*, *38*(7), 8384–8391. https://doi.org/10.1016/j.eswa.2011.01.031

Dolan, J. G., Isselhardt, B. J., & Cappuccio, J. D. (1989). The Analytic Hierarchy Process in Medical Decision Making: A Tutorial. *Medical Decision Making, 9*(1), 40–50. https://doi.org/10.1177/0272989x8900900108

Dožić, S., & Kalić, M. (2014). An AHP approach to aircraft selection process. *Transportation Research Procedia, 3,* 165–174. https://doi.org/10.1016/j.trpro.2014.10.102

Dožić, S., & Kalić, M. (2015). Comparison of two MCDM methodologies in aircraft type selection problem. *Transportation Research Procedia*, *10*, 910–919. https://doi.org/10.1016/j.trpro.2015.09.044

Dožić, S., & Kalić, M. (2015). Three-stage airline fleet planning model. *Journal of Air Transport Management, 46,* 30–39. https://doi.org/10.1016/j.jairtraman.2015.03.011

Dožić, S., Lutovac, T., & Kalić, M. (2018). Fuzzy AHP approach to passenger aircraft type selection. *Journal of Air Transport Management, 68,* 165–175. https://doi.org/10.1016/j.jairtraman.2017.08.003

European Union Aviation Safety Agency. (2009). *EASA 2009.OP.23 SAPOX study report*. https://www.easa.europa.eu/sites/default/files/dfu/4RET0706%20ed6%20-%20SAPOX%20Study%20Report%20111005.pdf

European Union Aviation Safety Agency. (2014, October 15). *EASA certifies Airbus A350 XWB for up to 370 minute ETOPS.* https://www.easa.europa.eu/newsroom-and-events/news/easa-certifies-airbus-a350-xwb-370-minute-etops

European Union Aviation Safety Agency. (2020). *Certification specifications and acceptable means of compliance for large aeroplanes CS-25*. https://www.easa.europa.eu/sites/default/files/dfu/cs-25_amendment_26_0.pdf

Federal Aviation Administration. (n.d.-a). *Accident overview: Extended operations (ETOPS). https://lessonslearned.faa.gov/ll_main.cfm?TabID=4&LLID=73&LLTypeID=2#null*

Federal Aviation Administration. (n.d.-b). *Introduction to aviation physiology*. https://www.faa.gov/pilots/training/airman_education/media/IntroAviationPhys.pdf

Franssen, E. A. M., van Wiechen, C. M. A. G., Nagelkerke, N. J. D., & Lebret, E. (2004). Aircraft noise around a large international airport and its impact on general health and medication use. *Occupational and Environmental Medicine*, *61*(5), 405–413. https://doi.org/10.1136/oem.2002.005488

GE Aviation. (n.d.). *GENX high bypass turbofan engines*. https://www.geaviation.com/sites/default/files/datasheet-genx.pdf

Gomes, L. F., de Mattos Fernandes, J. E., & de Mello, J. C. (2012). A fuzzy stochastic approach to the multicriteria selection of an aircraft for regional chartering. *Journal of Advanced Transportation*, *48*(3), 223–237. https://doi.org/10.1002/atr.206

Goossens, A. J. M., & Basten, R. J. I. (2015). Exploring maintenance policy selection using the analytic hierarchy process; An application for naval ships. *Reliability Engineering & System Safety*, *142*, 31–41. https://doi.org/10.1016/j.ress.2015.04.014

Hepher, T. (2019, June 17). *Airbus faces cabin comfort dilemma as it launches A321XLR jet*. Reuters. https://www.reuters.com/article/us-france-airshow-airbus-cabin-idUSKCN1TI0LN

Hwang, C. L., & Yoon, K. (1981). *Multiple attribute decision making methods and applications: A state-of-the art survey*. Springer-Verlag.

Ilgın, M. A. (2019). Aircraft selection using linear physical programming. *Journal of Aeronautics and Space Technologies*, *12*(2).

International Air Transport Association. (n.d.). *Climate change: Working towards ambitious targets*. https://www.iata.org/en/programs/environment/climate-change/

International Air Transport Association. (2019). *Annual review 2019*. https://www.iata.org/contentassets/c81222d96c9a4e0bb4ff6ced0126f0bb/iata-annual-review-2019.pdf

International Air Transport Association. (2020). *World air transport statistics 2020.* https://valordaaviacao.org.br/wp-content/uploads/2020/12/World-Air-Transport-Statistics-2020.pdf

International Air Transport Association. (2021a). *Industry statistics.* https://www.iata.org/en/iata-repository/pressroom/fact-sheets/industry-statistics/

International Air Transport Association. (2021b). *Jet fuel price monitor.* https://www.iata.org/en/publications/economics/fuel-monitor

International Air Transport Association. (2021c). *20 year passenger forecast infographic.* https://www.iata.org/contentassets/e938e150c0f547449c1093239597cc18/pax-forecast-infographic-2020-final.pdf

International Civil Aviation Organization. (n.d.-a). *Aircraft noise*. https://www.icao.int/environmental-protection/Pages/noise.aspx

International Civil Aviation Organization. (n.d.-b). *Future of Aviation*. https://www.icao.int/Meetings/FutureOfAviation/Pages/default.aspx

International Civil Aviation Organization. (n.d.-c). *Reduction of Noise at Source.* https://www.icao.int/environmental-protection/Pages/Reduction-of-Noise-at-Source.aspx

International Civil Aviation Organization. (n.d.-d). *ICAO Noise Data Base.* http://noisedb.stac.aviation-civile.gouv.fr/pdf/11167

International Civil Aviation Organization. (n.d.-e). *ICAO Noise Data Base.* http://noisedb.stac.aviation-civile.gouv.fr/pdf/11223

International Civil Aviation Organization. (2014). *EDTO workshop.* https://www.icao.int/SAM/Documents/2014-EDTO/EDTO%20Module%20%204%20%E2%80%93%20Aircraft%20certification%20considerations.pdf

International Civil Aviation Organization. (2017a). *Airline operating costs and productivity*. https://www.icao.int/mid/documents/2017/aviation%20data%20and%20anal ysis%20seminar/ppt3%20-%20airlines%20operating%20costs%20and%20productivity.pdf

International Civil Aviation Organization. (2017b). *Annex 16 - Environmental Protection: Volume I - Aircraft Noise* (8th ed.).

International Civil Aviation Organization. (2017c). *Extended diversion time operations (EDTO) manual.* https://www.icao.int/MID/Documents/2020/EDTO%20Workshop/10085_cons_en.pdf

International Civil Aviation Organization. (2018). *ICAO Noise Data Base.* http://noisedb.stac.aviation-civile.gouv.fr/pdf/13389

International Civil Aviation Organization. (2019). *ICAO Noise Data Base.* http://noisedb.stac.aviation-civile.gouv.fr/pdf/6107

Johnson, V. S. (1990). Minimizing life cycle cost for subsonic commercial aircraft. *Journal of Aircraft*, *27*(2), 139–145. https://doi.org/10.2514/3.45909

Kahraman, C., Cebeci, U., & Ulukan, Z. (2003). Multi-criteria supplier selection using Fuzzy AHP. *Logistics Information Management*, *16*(6), 382–394. https://doi.org/10.1108/09576050310503367

Khazai, B., Merz, M., Schulz, C., & Borst, D. (2013). An integrated indicator framework for spatial assessment of industrial and social vulnerability to indirect disaster losses. *Natural Hazards*, *67*(2), 145–167. https://doi.org/10.1007/s11069-013-0551-z

Kiracı, K., & Akan, E. (2020). Aircraft selection by applying AHP and TOPSIS in interval type-2 fuzzy sets. *Journal of Air Transport Management*, *89*, 101924. https://doi.org/10.1016/j.jairtraman.2020.101924

Kiracı, K., & Bakır, M. (2018). Application of commercial aircraft selection in aviation industry through multi-criteria decision making methods. *Celal Bayar Üniversitesi Sosyal Bilimler Dergisi*, *16*(4), 307–332. https://doi.org/10.18026/cbayarsos.505987

Law Library of Congress. (2020). *Airport noise regulations*. https://tile.loc.gov/storage-services/service/ll/llglrd/2019713400/2019713400.pdf

Lufthansa. (2019). *Balance: Sustainability report 2019.* https://www.lufthansagroup.com/media/downloads/en/responsibility/LH-sustainability-report-2019.pdf

Lund, M. T., Aamaas, B., Berntsen, T., Bock, L., Burkhardt, U., Fuglestvedt, J. S., & Shine, K. P. (2017). Emission metrics for quantifying regional climate impacts of Aviation. *Earth System Dynamics*, *8*(3), 547–563. https://doi.org/10.5194/esd-2017-11

Muhm, J. M., Rock, P. B., McMullin, D. L., Jones, S. P., Lu, I. L., Eilers, K. D., Space, D. R., & McMullen, A. (2007). Effect of aircraft-cabin altitude on passenger discomfort. *New England Journal of Medicine*, *357*(1), 18–27. https://doi.org/10.1056/nejmoa062770

National Aeronautics and Space Administration. (2010). *NASA helps create a more silent night.* https://www.nasa.gov/topics/aeronautics/features/bridges_chevron_events.html

Olson, D. L. (2004). Comparison of weights in TOPSIS models. *Mathematical and Computer Modelling*, *40*(7-8), 721–727. https://doi.org/10.1016/j.mcm.2004.10.003

Ortiz-Barrios, M., Miranda-De la Hoz, C., López-Meza, P., Petrillo, A., & De Felice, F. (2019). A case of food supply chain management with AHP, DEMATEL, and TOPSIS. *Journal of Multi-Criteria Decision Analysis, 27*(1-2), 104–128. https://doi.org/10.1002/mcda.1693

Özdemir, Y., & Başlıgil, H. (2016). Aircraft selection using fuzzy ANP and the generalized choquet integral method: The Turkish airlines case. *Journal of Intelligent & Fuzzy Systems*, *31*(1), 589–600. https://doi.org/10.3233/ifs-162172

Özdemir, Y., Başlıgil, H., Karaca, M. (2011, July 6-8). *Aircraft Selection Using Analytic Network Process: A Case for Turkish Airlines* [Paper presentation]. WCE 2011, London, United Kingdom.

Pamučar, D., & Ćirović, G. (2015). The selection of transport and handling resources in logistics centers using Multi-Attributive Border Approximation Area Comparison (MABAC). *Expert Systems with Applications, 42*(6), 3016–3028. https://doi.org/10.1016/j.eswa.2014.11.057

Ravi, V., Shankar, R., & Tiwari, M. K. (2005). Analyzing alternatives in reverse logistics for end-of-life computers: ANP and Balanced Scorecard Approach. *Computers & Industrial Engineering*, *48*(2), 327–356. https://doi.org/10.1016/j.cie.2005.01.017

Rolls-Royce. (2016). *Trent 7000*. https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/civil-aerospace-downloads/trent-7000-infographic.pdf

Rolls-Royce. (2018). *Trent XWB*. https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/civil-aerospace-downloads/trent-xwb-infographic.pdf

Roszkowska, E. (2011). Multi-criteria decision making models by applying the TOPSIS method to crisp and interval data. In T. Trzaskalik & T. Wachowicz (Eds.), *Multiple criteria decision making '10-11* (pp. 200-230). Publisher of The University of Economics in Katowice.

Saaty, T. L. (1983). Priority setting in complex problems. *IEEE Transactions on Engineering Management*, *EM-30*(3), 140–155. https://doi.org/10.1109/tem.1983.6448606

Saaty, T. L. (1988). What is the analytic hierarchy process?. In G. Mitra, H. J. Greenberg, F. A. Lootsma, M. J. Rijkaert, H. J. Zimmermann (Eds.), *Mathematical models for decision support. NATO ASI series (series f: computer and systems sciences)* (Vol. 48, pp. 109-121). Springer. https://doi.org/10.1007/978-3-642-83555-1_5

Saaty, T. L. (1989) Group decision making and the AHP. In B. L. Golden, E. A. Wasil, P. T. Harker (Eds.), *The analytic hierarchy process*: *Applications and studies*. (Vol. 1, pp. 59-67). Springer. https://doi.org/10.1007/978-3-642-50244-6_4

Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, *48*(1), 9–26. https://doi.org/10.1016/0377-2217(90)90057-i

Saaty, T. L. (1995). Transport planning with multiple criteria: The analytic hierarchy process applications and progress review. *Journal of Advanced Transportation*, *29*(1), 81–126. https://doi.org/10.1002/atr.5670290109

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences*, *1*(1), 83. https://doi.org/10.1504/ijssci.2008.017590

Saaty, T. L., & Tran, L. T. (2007). On the invalidity of fuzzifying numerical judgments in the analytic hierarchy process. *Mathematical and Computer Modelling*, *46*(7-8), 962–975. https://doi.org/10.1016/j.mcm.2007.03.022

Saaty, T. L., & Vargas, L. G. (2012). *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process* (2nd ed.). Springer. https://doi.org/10.1007/978-1-4614-3597-6

Sara, J., Stikkelman, R. M., & Herder, P. M. (2015). Assessing relative importance and mutual influence of barriers for CCS deployment of the ROAD project using AHP and DEMATEL methods. *International Journal of Greenhouse Gas Control*, *41*, 336–357. https://doi.org/10.1016/j.ijggc.2015.07.008

See, T.-K., Gurnani, A., & Lewis, K. (2004). Multi-Attribute Decision Making Using Hypothetical Equivalents and Inequivalents. *Journal of Mechanical Design*, *126*(6), 950–958. https://doi.org/10.1115/1.1814389

Seker, S., & Zavadskas, E. (2017). Application of Fuzzy DEMATEL Method for Analyzing Occupational Risks on Construction Sites. *Sustainability*, *9*(11), 2083. https://doi.org/10.3390/su9112083

Si, S.-L., You, X.-Y., Liu, H.-C., & Zhang, P. (2018). DEMATEL Technique: A Systematic Review of the State-of-the-Art Literature on Methodologies and Applications. *Mathematical Problems in Engineering*, *2018*, 1–33. https://doi.org/10.1155/2018/3696457

Sun, X., Gollnick, V., & Stumpf, E. (2011). Robustness Consideration in Multi-Criteria Decision Making to an Aircraft Selection Problem. *Journal of Multi-Criteria Decision Analysis*, *18*(1-2), 55–64. https://doi.org/10.1002/mcda.471

Şener, Z., Yılanlı, M. (2019, December 13-15). *Determining Aircraft Selection Criteria Weights in Airline Industry.* [Paper presentation]. MAC 2019, Prague, Czech Republic.

Triantaphyllou, E. (2000). *Multi-criteria decision making methods: A comparative study* (Vol. 44). Springer.

Tzeng, G.-H., & Huang, J.-J. (2012). *Multiple attribute decision making: Methods and applications*. CRC Press.

United States Bureau of Labor Statistics. (2021). *Aircraft and avionics equipment mechanics and technicians*. https://www.bls.gov/ooh/installation-maintenance-and-repair/aircraft-and-avionics-equipment-mechanics-and-technicians.htm

United States Environmental Protection Agency. (2021). *Global greenhouse gas emissions data.* https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. *European Journal of Operational Research, 169*(1), 1-29. doi:10.1016/j.ejor.2004.04.028

Vargas, R. V. (2010). *Using the analytic hierarchy process (AHP) to select and prioritize projects in a portfolio* [Paper presentation]. PMI® Global Congress 2010—North America, Washington, DC, United States.

Vasconcelos Oliveira, J. M. (2015). *Development of operating cost models for the preliminary design optimization of an aircraft* [Master's thesis, Tecnico Lisboa].

Wang, W.-C., Lin, Y.-H., Lin, C.-L., Chung, C.-H., & Lee, M.-T. (2012). DEMATEL-based model to improve the performance in a matrix organization. *Expert Systems with Applications*, *39*(5), 4978–4986. https://doi.org/10.1016/j.eswa.2011.10.016

Wu, H.-H., & Tsai, Y.-N. (2012). An integrated approach of AHP and DEMATEL methods in evaluating the criteria of auto spare parts industry. *International Journal of Systems Science*, *43*(11), 2114–2124. https://doi.org/10.1080/00207721.2011.564674

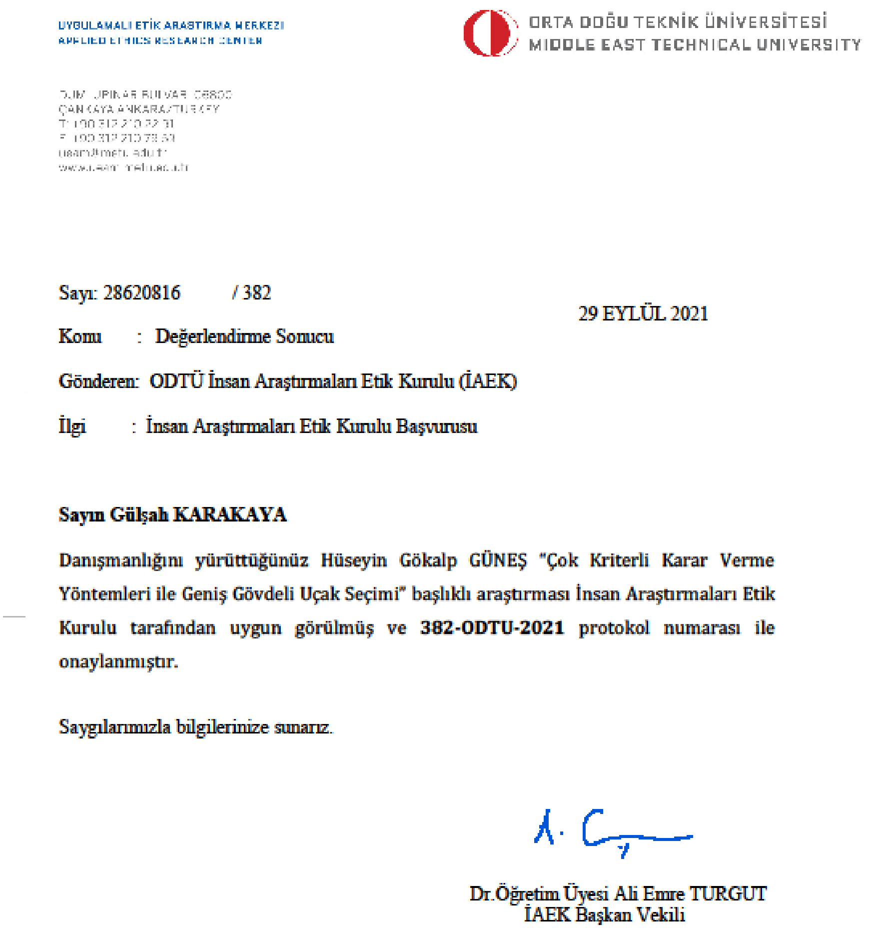
Wu, W.-W. (2008). Choosing knowledge management strategies by using a combined ANP and DEMATEL approach. *Expert Systems with Applications*, *35*(3), 828–835. https://doi.org/10.1016/j.eswa.2007.07.025

Wu, W.-W., & Lee, Y.-T. (2007). Developing global managers' competencies using the fuzzy DEMATEL method. *Expert Systems with Applications*, *32*(2), 499–507. https://doi.org/10.1016/j.eswa.2005.12.005

Yeh, C.-H., & Chang, Y.-H. (2009). Modeling subjective evaluation for fuzzy group multicriteria decision making. *European Journal of Operational Research*, *194*(2), 464–473. https://doi.org/10.1016/j.ejor.2007.12.029

APPENDICES

A. APPROVAL OF THE METU HUMAN SUBJECTS ETHICS COMMITTEE



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29 EYLÜL 2021

Konu : Değerlendirme Sonucu

Gönderen: ODTÜ İnsan Araştırmaları Etik Kurulu (İAEK)

İlgi : İnsan Araştırmaları Etik Kurulu Başvurusu

Sayın Gülşah KARAKAYA

Danışmanlığını yürüttüğünüz Hüseyin Gökalp GÜNEŞ "Çok Kriterli Karar Verme Yöntemleri ile Geniş Gövdeli Uçak Seçimi" başlıklı araştırması İnsan Araştırmaları Etik Kurulu tarafından uygun görülmüş ve **382-ODTU-2021** protokol numarası ile onaylanmıştır.

Saygılarımızla bilgilerinize sunarız.

Dr.Öğretim Üyesi Ali Emre TURGUT
İAEK Başkan Vekili

B. PCMs OF ECONOMICS MAIN CRITERION, ENVIRONMENTAL IMPACT AND PASSENGER COMFORT SUB-CRITERIA

Economics	**Price**	**DOC**
Price	1.00	0.48
DOC	2.08	1.00

Environmental Impact	**CO_2 Emission**	**Noise Level**
CO_2 Emission	1.00	3.66
Noise Level	0.27	1.00

Passenger Comfort	**Cabin Vol. per Seat**	**Cabin Altitude**
Cabin Vol. per Seat	1.00	1.44
Cabin Altitude	0.69	1.00

C. NORMALIZED PCMs

Main Criteria	Economics	Technical Characteristics	Environmental Impact	Passenger Comfort
Economics	0.53	0.65	0.42	0.35
Technical Characteristics	0.19	0.24	0.42	0.41
Environmental Impact	0.13	0.06	0.10	0.14
Passenger Comfort	0.15	0.06	0.07	0.10

Economics	Price	DOC
Price	0.32	0.32
DOC	0.68	0.68

Technical Characteristics	Range	Seat Capacity	Cargo Capacity	Reliability
Range	0.13	0.06	0.15	0.20
Seat Capacity	0.43	0.20	0.23	0.17
Cargo Capacity	0.08	0.08	0.09	0.09
Reliability	0.36	0.66	0.54	0.55

Environmental Impact	**CO_2 Emission**	**Noise Level**
CO_2 Emission	0.79	0.79
Noise Level	0.21	0.21

Passenger Comfort	**Cabin Vol. per Seat**	**Cabin Altitude**
Cabin Vol. per Seat	0.59	0.59
Cabin Altitude	0.41	0.41

D. NORMALIZED DRM

	PR	DOC	RA	SC	CC	RE	CO_2	NL	CV	CA
PR	0.000	0.138	0.123	0.138	0.108	0.092	0.108	0.108	0.062	0.000
DOC	0.154	0.000	0.154	0.154	0.123	0.123	0.138	0.092	0.062	0.000
RA	0.123	0.138	0.000	0.123	0.138	0.046	0.077	0.062	0.062	0.015
SC	0.123	0.123	0.123	0.000	0.108	0.046	0.077	0.062	0.108	0.000
CC	0.092	0.108	0.123	0.108	0.000	0.046	0.062	0.062	0.046	0.000
RE	0.123	0.138	0.092	0.062	0.092	0.000	0.077	0.062	0.015	0.000
CO_2	0.138	0.138	0.108	0.092	0.092	0.031	0.000	0.031	0.031	0.000
NL	0.077	0.046	0.062	0.046	0.077	0.031	0.031	0.000	0.015	0.000
CV	0.092	0.077	0.092	0.123	0.092	0.015	0.031	0.031	0.000	0.000
CA	0.031	0.031	0.046	0.046	0.046	0.000	0.000	0.000	0.000	0.000

E. NORMALIZED DECISION MATRIX

	PR	DOC	RA	SC	CC	RE	CO2	NL	CV	CA
787-8	0.428	0.436	0.484	0.416	0.419	0.500	0.514	0.317	0.521	0.468
787-9	0.505	0.501	0.499	0.499	0.539	0.500	0.480	0.443	0.505	0.468
A330-900	0.511	0.520	0.477	0.533	0.494	0.432	0.527	0.787	0.429	0.585
A350-900	0.548	0.538	0.537	0.542	0.539	0.560	0.478	0.289	0.538	0.468

F. TURKISH SUMMARY / TÜRKÇE ÖZET

GİRİŞ

Hava yolu taşımacılığı son yıllarda yolcu sayıları bakımından sürekli olarak büyüme kaydeden bir ulaşım yolu olmuştur. Uluslararası Sivil Havacılık Örgütü (ICAO, n.d.-b), hava yolu endüstrisinin 1995 ve 2015 yılları arasında yolcu sayılarındaki bileşik yıllık büyüme oranının %5,4 olduğunu belirtmiştir. COVID-19 salgınının küresel çapta uçuş sayılarında yol açtığı düşüşe rağmen Uluslararası Hava Taşımacılığı Birliği (IATA, 2021c) hava yolu taşımacılığında salgın öncesi koşullara 2023'e kadar dönüleceğini tahmin etmektedir. Bununla beraber, Airbus (2021d) ve Boeing (2021a), hava trafik seviyelerinin önümüzdeki 20 yıl boyunca ortalama %3,9 ila %4,0 arasında büyüyeceğini tahmin etmektedir. Ayrıca Boeing, bu süre içerisinde toplam 43.610 yeni uçağa ihtiyaç duyulacağını ve bunların 7.670 tanesinin geniş gövdeli yolcu uçağı olacağını öngörmektedir. Hava yolu firmaları artan talebi karşılamak ve ellerinde bulunan filolarını yenilemek amacıyla yeni uçaklara ve bunu gerçekleştirmek için başarılı filo planlama süreçlerine ihtiyaç duymaktadır.

Hava yolları açısından filo planlama, şirketlerin mevcut ve gelecekteki uçuş noktalarına kapasite sağlamak amacı ile uçak edinmesinin sağlandığı bir iş sürecidir (Clark, 2007). Uçak satın alım süreçleri hava yolları için büyük yatırımlar olduğundan ve satın alınan uçaklar hava yollarının karlılığında büyük öneme sahip olduğundan filo planlama stratejik bir öneme sahiptir.

Bir uçak tipinin seçilmesi, çeşitli kriterlerin değerlendirilmesini gerektirse de Belobaba ve diğerleri (2016), havayollarının genellikle bu karar problemine finansal açıdan yaklaştıklarını belirtmekte ve diğer uçak özelliklerinin de hesaba katılmasının önemli olduğunu savunmaktadır. Çeşitli kriter ve alternatifi içinde barındıran karmaşık bir süreç olması nedeniyle yolcu uçağı seçimi problemi çok kriterli karar verme (ÇKKV) problemi olarak nitelendirilebilir. Bu problem son yıllarda araştırmacılar tarafından artan bir ilgi görmektedir.

Literatürde ÇKKV yöntemlerini kullanarak uçak seçim problemini inceleyen farklı çalışmalar bulunmaktadır. Bunlar arasında kullanılan kriterler ve kriterler arasındaki etkileşim konusu gibi belirli iyileştirme alanları bulunmaktadır. Bu çalışmada, geniş gövdeli yolcu uçağı seçimi ile ilgili kapsamlı bir kriter seti kullanılmış ve yeni bir kriter olan kabin irtifası eklenmiştir. Bu çalışma, kullanılan kriterlerin ağırlık değerlerinin bulunabilmesi için Analitik Hiyerarşi Süreci (AHS) ve Decision Making Trial and Evaluation Laboratory (DEMATEL) adlı iki farklı ÇKKV yönteminin kullanılmasını içermektedir. Bu yöntemlerle elde edilen iki farklı kriter ağırlıkları seti başka bir ÇKKV yöntemi olan Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) ile birlikte kullanılmıştır. AHS-TOPSIS ve DEMATEL-TOPSIS yaklaşımları kullanılarak geniş gövdeli yolcu uçağı seçim problemi çözülmüş ve kriter bağımsızlığı varsayımının etkileri araştırılmıştır. Kriterler arasındaki etkileşim konusu DEMATEL yöntemi ile incelenmiş ve kriterlerin birbirleri üzerindeki etkileri etki ilişki haritaları (EİH) ile gösterilmiştir. Bilindiği kadarıyla DEMATEL-TOPSIS yaklaşımı ve kriterlerin EİH'lerinin çıkarılması uçak seçimi probleminde ilk olarak bu tezde ele alınmıştır. Bu çalışma, bu karmaşık probleme bir çözüm sunarak hava yolu şirketlerine ve karar vericilere (KV) filo planlama süreçlerinde karar desteği sunmayı amaçlamaktadır.

KAYNAK TARAMASI

Yeh ve Chang (2009) yerel bir Tayvan hava yolu şirketinin uçak seçimi için beş farklı uçağı bulanık grup ÇKKV yöntemi ile değerlendirmiştir. Çalışmada on bir alt kriter üç ana kriter altında gruplandırılmış ve kriterlerin ağırlıklarını elde edebilmek için ikili karşılaştırmalar kullanılmıştır. Yazarlar, alternatiflerin performans değerlerini bulmak için KV'lerin değerlendirmelerinden faydalanmışlardır. KV'lerin verdiği kararların öznelliğinden kaynaklanabilecek hataları ele almak için ise üçgensel bulanık sayıları kullanmışlardır. KV'lerin bireysel değerlendirmeleri geometrik ortalama yöntemi ile toplanmıştır. Yazarlar alternatifleri sıralamak için değiştirilmiş bir TOPSIS yöntemi önermişlerdir. Buna göre yazarlar, normalleştirilmiş karar matrisi kullanmak yerine, elde ettikleri kriter ağırlıklarını kullanarak alternatiflerin pozitif ve negatif ideal çözümlerden olan ağırlıklı uzaklıklarını hesaplamışlardır.

Bruno ve diğerleri (2015) Air Italy'nin bölgesel yolcu uçağı gereksinimini incelemek için AHS ve bulanık küme teorisinin bir kombinasyonunu kullanmışlardır. Çalışmada, alternatifler konusunda hava yolunun gereksinimleri göz önünde bulundurulmuş ve üç alternatifin incelenmesi önerilmiştir. Kriterlerin belirlenmesi için hava yolunun ihtiyaçları ile birlikte havacılık literatürü kullanılmış ve çalışmada dört ana kriter altında sekiz alt kriter kullanılmıştır. Kriterlerin önemlerinin değerlendirilmesi ve ağırlıklarının AHS yöntemi ile elde edilmesi için Air Italy'den dört uzmanın yer aldığı bir odak grubuna danışılmıştır. Ayrıca, bu uzmanlardan alternatif uçakların performans seviyelerini sözlü bir ölçeğe göre değerlendirmeleri istenmiştir. Sonrasında AHS ve bulanık küme yöntemi birleştirilerek uçaklar puanlanmış ve sıralanmıştır. Bu çalışmada çevresel etki ana kriteri ilk kez kullanılmıştır. Ancak uçak menzili, yolcu kapasitesi, kargo kapasitesi ve güvenilirlik gibi önemli teknik özellikler kullanılmamıştır.

Dozic ve Kalic (2015b), Belgrad havaalanından faaliyet gösteren farazi bir hava yolu için filo planlama sürecini filo bileşimi, filo büyüklüğü ve uçak seçim adımlarına bölerek bir model oluşturmuşlardır. Yazarlar, kısa ve orta menzilli rotalar için uygun uçak kategorilerini ve gereken uçak sayısını belirledikten sonra alternatifler arasından uygun olanı seçmek için Even Swaps adlı yöntemi kullanmışlardır. Yazarlar, alternatifleri yolcu kapasitesine göre küçük ve orta olmak üzere iki kategoriye ayırmışlardır. Modelde yolcu kapasitesi, uçak fiyatı, maksimum kalkış ağırlığı, bagaj/yolcu ve birim maliyetler olmak üzere beş farklı değerlendirme kriteri kullanılmıştır. Çalışmada küçük uçak kategorisi için ATR 72-600, büyük uçak kategorisi için ise Airbus A319neo en iyi alternatifler olarak belirlenmiştir. Dozic ve Kalic (2015a), bir diğer çalışmalarında ödeme koşulları kriterini de dahil ederek Even Swaps ve AHS yöntemlerini küçük uçak kategorisi özelinde karşılaştırmışlardır. Bu çalışmada iki yöntem ile de aynı uçağın en iyi olarak değerlendirildiği gösterilmiştir.

Özdemir ve Başlıgil (2016), Türk Hava Yolları'nın uçak seçimi için bulanık Analitik Ağ Süreci (AAS) ve Choquet integral yöntemlerini kullanmışlardır. Yazarlar bu yöntemleri kriterlerin bağımlılığı ve kriterler arasındaki etkileşim ile çalışmaya olanak vermesi nedeni ile seçtiklerini savunmuşlardır. Çalışmada maliyetler, fiziksel özellikler ve diğerleri ve zaman olmak üzere üç ana kriter ve on alt kriter kullanılmıştır. Çalışma sonuçlarının geçerliliğini ölçmek adına bulanık AHS yöntemi kullanılmıştır.

Üç dar gövdeli yolcu uçağının değerlendirildiği çalışmada birinci seçilen uçak üç yöntemde de değişmemiş, ancak yöntemler arasında sıralama farklılıkları oluşmuştur. Çalışmada uzmanlardan istenen fazla sayıdaki ikili karşılaştırmanın yol açtığı karmaşıklık, yazarlar tarafından da belirtilen bir kısıt oluşturmuştur.

Kiracı ve Akan (2020) çalışmalarında hava yolu firmalarının uçak seçimi için bulanık AHS ve bulanık TOPSIS yöntemlerini kullanmışlardır. Çalışmada, literatürde kullanılmış olan on üç alt kriter belirlenmiş ve teknik, ekonomik ve çevre ana kriterleri altında gruplandırılmıştır. Yazarlar öncelikle bulanık AHS yöntemini kullanarak beş alt kriteri ağırlıkları nedeniyle elemiş, ardından tekrar aynı yöntemle ağırlıklarını hesaplamışlardır. Dört orta menzilli dar gövdeli uçağın dahil olduğu çalışmada alternatiflerin performans değerleri uzmanların sözlü değerlendirmeleriyle belirlenmiş ve bulanık TOPSIS sonuçlarına göre Airbus A321neo ilk sırada yer almıştır.

ÇKKV yöntemleri kullanarak uçak seçimi problemini inceleyen çalışmalardan yalnızca birkaçında kriter bağımlılığından söz edilmiştir. Yeh ve Chang (2009), çalışmalarında aralarında güvenilirlik, uçuş menzili, yolcu tercihi, gürültü seviyesi, doğrudan operasyon maliyeti ve fiyat gibi kriterlerin de bulunduğu on bir alt kriterin birbirinden bağımsız olduğunu belirtmişlerdir. Özdemir ve diğerleri (2011) Türk Hava Yolları'nın uçak seçimi için yaptıkları çalışmada kriterler arasındaki etkileşimin problemin çözümüne dahil edilebilmesini sağlayan AAS yöntemini kullanmışlardır. Bir önceki uçak seçimi çalışmalarından farklı olarak bulanık AAS ve bulanık AHS yöntemlerinin sonuçlarını karşılaştıran Özdemir ve Başlıgil (2016), alternatiflerin elde ettiği puanlardaki farklılığı bulanık AHS yönteminde kriterlerin bağımsız olduğu varsayımında bulunulmasına dayandırmışlardır. Şener ve Yılanlı (2019) çalışmalarında kriterler arası etkileşimin ölçülebilmesine olanak sağlayan DEMATEL yöntemini kullanmış ve uçak seçim kriterlerinin ağırlıklarını belirlemişlerdir.

Yapılan kaynak taraması ile uçak seçim çalışmalarında kullanılan kriterlerin belirlenmesi sağlanmıştır. Özellikle son yıllarda yapılan çalışmalarda çevresel etki kriterlerinin de uçak seçim problemlerine dahil edildiği görülmüştür. Çalışmalarda değerlendirme kriterlerinin sayısının üç ve on dört arasında değiştiği saptanmıştır. Bir taraftan modelde az sayıda kriterin kullanılması problemin tam anlamıyla yansıtılmasını engelleyebilecekken, çok sayıda kriterin kullanımı modeli gereğinden fazla karmaşıklaştırabilir. Bu neden gözetilerek bu çalışmada hava yollarının geniş gövdeli uçak seçim sürecini uygun biçimde yansıtacak bir kriter seti kullanılmıştır. Bu kriterler ekonomik, teknik özellikler, çevresel etki ve yolcu konforu adlı dört ana kriter altında gruplandırılmıştır.

Uçak seçim çalışmalarında AHS ve bulanık AHS yöntemlerinin araştırmacılar tarafından sıklıkla kullanıldığı görülmüştür. Araştırmacıların bir kısmı (Bruno ve diğerleri, 2015; Dozic & Kalic, 2014; Dozic ve diğerleri, 2018; Özdemir & Başlıgil, 2016) bu yöntemlerden birini uçak seçimi için kullanmışken, bir kısmı ise (Ahmed ve diğerleri, 2020; Kiracı & Akan, 2020; Kiracı & Bakır, 2018a; Sun ve diğerleri, 2011) yine bu problemdeki kriterlerin ağırlıklarının belirlenebilmesi için kullanmışlardır. Bu çalışmada da AHS yöntemi kriter ağırlıklarının bulunabilmesi ve kriter bağımsızlığı varsayımının sonuçlar üzerindeki olası etkisinin ölçülebilmesi için kullanılmıştır.

Kriterler arasındaki bağımlılığın AAS yöntemi ile ele alınabileceği bilinmektedir. Ancak bu yöntem Ravi ve diğerlerinin (2005) belirttiği bazı dezavantajlara sahiptir. Yazarlar bu yöntemin uzmanlar tarafından yapılması gereken ikili karşılaştırma sayısını önemli ölçüde artırdığını, bunun da hem zaman kaybı yarattığını hem de gerekli işlem sayısını artırdığını belirtmişlerdir. Bu nedenle bu çalışmada AAS yöntemi kullanılmamıştır.

Literatürde yaygın bir şekilde kullanılan bulanık sayılar bu çalışmada hesaplamalarda gereksiz karmaşıklık yaratmaması için kullanılmamıştır. Saaty ve Tran (2007) çalışmalarında bulanık sayıların kullanımının çözümlerin geçerliliğini artırmayacağını, aksine uzmanlar tarafından yapılan değerlendirmeleri daha da belirsizleştireceğini savunmuşlardır.

YÖNTEM

AHS Yöntemi

Thomas L. Saaty tarafından 1970’lerde geliştirilen AHS, KV’lerin değerlendirmelerinin kullanılarak bir unsurun bir başka unsura kıyasla ne derecede daha önemli olduğunun ölçüldüğü ve bu sayede unsurların ağırlık değerlerinin hesaplandığı bir ÇKKV yöntemidir (Saaty, 2008). Bu çalışmada AHS yöntemi kriterlerin ağırlıklarını belirlemek amacıyla kullanılmıştır.

AHS yönteminin ilk adımı problemin tanımlanmasını gerektirmektedir. Problemin amacının, kriterlerinin (ve alt kriterlerinin) ve alternatiflerinin belirlenmesi ile karmaşık bir yapıya sahip olan problem seviyelere ayrılır ve karar hiyerarşisi oluşturulur. Bu işlem uygulanırken dikkat edilmesi gereken bir nokta aynı seviyede bulunan unsurların birbirleri ile kıyaslanabilir olması gerekliliğidir.

Ana kriterler ve alt kriterler birbirinden ayrı seviyelere ayrıldıktan ve alt kriterler ortak bir ana kriter altında gruplandıktan sonra ikili karşılaştırma matrisleri (İKM) oluşturulur. İkili karşılaştırmalar ile ana kriterler ve bir ana kritere bağlı bulunan alt kriterler birbirleri arasında hiyerarşide bulunan bir üst seviyeye göre kıyaslanırlar. Kıyaslama yapılırken Saaty'nin (1990) 1'den 9'a kadar olan ölçeği kullanılır. Bu ölçekte 1 "eşit derecede önemli", 9 ise "son derece önemli" anlamına gelmektedir. Karşılaştırılacak olan n sayıda kriter için $n\ x\ n$ boyutunda bir matris oluşturulur. Bu matriste a_{ij}, kriter i'nin kriter j'ye kıyasla ne kadar önemli olduğunu belirtir ve a_{ji}, a_{ij} değerinin tersine eşittir. Matriste bulunan köşegen elemanları kriterlerin kendileri ile karşılaştırmalarının değerini göstereceğinden bu elemanlar bire eşit olur.

İkili karşılaştırmalar yapıldıktan sonra değerlendirmelerin ne derece tutarlı olduğu hesaplanır. Bunun için AHS tarafından tanımlanan tutarlılık endeksinin hesaplanması gerekir. Bir İKM'nin tutarlılık endeksi o matrisin boyutu ve matrisin en büyük özdeğeri olan λ_{max} kullanılarak hesaplanır. Tutarlılık endeksinin farklı matris boyutlarına göre verilmiş olan rastlantısal tutarlılık endeksine olan oranı tutarlılık oranını verir. Saaty (1983), tutarlılık oranı 0,10 ve altında olan İKM'lerin tutarlı sayılabileceğini, 0,20 ve altındaki değerlerin ise bazı durumlar için yeterli kabul edilebileceğini belirtmiştir. Bu değerin üzerindeki tutarlılık oranlarına sahip İKM'lerin ise tekrar gözden geçirilmesi gerektiğini belirtmiştir.

İkili olarak karşılaştırılan ana kriterlerin ağırlıklarının ve alt kriterlerin yerel ağırlıklarının belirlenebilmesi için İKM'ler kullanılır. Saaty ve Vargas (2012) ağırlıkların hesaplanmasında işlem karmaşıklığını önleyen bir yöntem önermişlerdir. Buna göre, İKM'nin sütun elemanları normalize edilir ve sonrasında her sıranın aritmetik ortalaması alınır. Böylece ağırlık vektörü elde edilir.

Ana kriterlerin ağırlıkları ve alt kriterlerin yerel ağırlıkları elde edildikten sonra, alt kriterlerin ağırlıkları hesaplanır. Bir alt kriterin ağırlığı, o alt kriterin yerel ağırlığı ile bağlı bulunduğu ana kriterin ağırlığının çarpımına eşittir.

DEMATEL Yöntemi

DEMATEL yöntemi bu çalışmada kriterler arası etkileşimi tespit etmek ve kriterlerin bağımlı ağırlıklarını hesaplamak için kullanılmıştır. Yöntemin adımlarının açıklanmasında Si ve diğerleri (2018) ve Wu (2008) çalışmalarından yararlanılmıştır.

DEMATEL yönteminin ilk adımında kriter i'nin kriter j üzerindeki doğrudan etkisi 0 (etkisiz) ve 4 (çok yüksek etki) arasında bir ölçekle uzmanlar tarafından değerlendirilir. İkili karşılaştırmalar yoluyla $n x n$ boyutlu doğrudan etki matrisi (DEM) oluşturulur. Ardından, DEM'in her bir elemanı, sütun ve satırların toplamlarının en büyüğüne bölünür ve matris normalize edilir.

Kriterlerin birbirleri üzerindeki toplam etkisini gösteren toplam ilişki matrisi (TİM), normalize edilmiş DEM ve birim matris kullanılarak oluşturulur. Bu matrisin elemanları kriter i'nin kriter j üzerindeki etkisinin büyüklüğünü gösterir.

Sonrasında TİM'in sıra ve sütunları toplanarak D ve R vektörleri oluşturulur. TİM'de $i = j$ sağlandığı zaman $(D_i - R_i)$ i kriterinin toplam etkisini, $(D_i - R_i)$ ise i kriterinin net etkisini gösterir. Kriterler arası ilişkilerin gösterilmesini sağlayan EİH'ler, kriterlerin $(D + R)$ ve $(D - R)$ değerlerinin sırasıyla grafiğin yatay ve düşey eksenleri boyunca yerleştirilmesiyle oluşturulur.

EİH'lerde sadece önemli kriter etkileşimlerini göstermek ve karmaşıklığı önlemek adına eşik değerleri kullanılır. TİM'deki ilişkilerden belirlenen eşik değerinin altında kalan bir değere sahip olan ilişkiler EİH'lerde gösterilmez. Eşik değeri, TİM'deki değerlerin ortalaması alınarak hesaplanır. Kriterler arası etkiler, değerlerinin büyüklüklerine göre ince ve kalın oklarla gösterilebilirler. Etkilerin bu şekilde sınıflandırılabilmesi için bu çalışmada ikinci bir eşik değeri kullanılmıştır.

DEMATEL yönteminin son adımında kriterlerin bağımlı ağırlıkları belirlenir. Bunun için bu çalışmada Dalalah ve diğerleri (2011) ve Pamučar ve Ćirović (2015) tarafından uygulanan ağırlık belirleme yöntemi kullanılmıştır. Bu yöntemde kriterlerin $(D_i + R_i)$ ve $(D_i - R_i)$ değerleri kullanılır.

TOPSIS Yöntemi

Bir ÇKKV yöntemi olan TOPSIS, Hwang ve Yoon (1981) tarafından geliştirilmiştir. TOPSIS yöntemi, mantıklı bir temele sahip olması, anlaşılabilir olması ve kullanıcılara kolaylık sağlaması gibi avantajlara sahiptir (Roszkowska, 2011). Kriter ağırlıklarının belirtilmesi dışında başka öznel bilgiye ihtiyaç duyulmayan yöntem, sayısal verilerle çalışmaya uygundur.

Yöntemin ilk aşamasında alternatiflerin her bir kriter için olan performans değerlerinin gösterildiği karar matrisi oluşturulur. Karar matrisinde d'_{ij}, alternatif i'nin, j kriterine göre olan performans değerini gösterir.

Karar matrisindeki performans değerleri farklı birimlere sahip olabilir. Bu değerlerin karşılaştırılabilmesi için değerler normalize edilir ve normalize edilmiş karar matrisi oluşturulur.

Yöntemin üçüncü aşamasında AHS ve DEMATEL yöntemleri ile belirlenmiş olan kriter ağırlıkları vektörü, normalize edilmiş karar matrisi ile çarpılarak ağırlıklı normalize edilmiş karar matrisi elde edilir.

TOPSIS yönteminde alternatiflerin performans değerleri kullanılarak pozitif ve negatif ideal çözümler hesaplanır. Bunun için kriterler öncelikle fayda ve maliyet kriterleri olarak gruplara ayrılır. Pozitif ideal çözüm, alternatiflerin fayda kriterleri altındaki en büyük değerleri ve maliyet kriterleri altındaki en küçük değerleri kullanılarak belirlenir. Diğer yandan negatif ideal çözüm, alternatiflerin fayda kriterleri altındaki en küçük değerleri ve maliyet kriterleri altındaki en büyük değerleri kullanılarak belirlenir.

Pozitif ve negatif ideal çözümler hesaplandıktan sonra alternatiflerin bu çözümlere olan uzaklıkları hesaplanır. Ardından, bu uzaklıklar kullanılarak alternatiflerin pozitif ideal çözüme olan bağıl yakınlıkları hesaplanır. Son olarak alternatifler pozitif ideal çözüme olan bağıl yakınlık değerlerine göre sıralanır ve en iyi alternatif belirlenir.

Kriter Tanımları

Ekonomik Özellikler

Hava yolu sektörü kar marjlarının göreceli olarak düşük olduğu bir sektördür. Uçak satın alımının hava yolları açısından büyük bir yatırım olması da göz önünde bulundurulduğunda, ekonomik özellikler önemli bir kriter olarak ortaya çıkmaktadır. Bir uçağın yaşam döngüsü maliyeti, uçağın fiyatı, doğrudan işletme giderleri (DİG) ve dolaylı işletme giderleri olmak üzere üç ana unsurdan oluşur (Johnson, 1990). Bunlar arasında uçak fiyatı ve DİG doğrudan uçak tipi ile ilgiliyken, dolaylı işletme giderleri hava yolu şirketlerinin işletimi ile ilgilidir. Bu nedenle bu çalışmada ilk iki gider kalemi ekonomik özellikler kriterinin altında incelenmiştir.

Fiyat

Hava yolu şirketleri yeni uçakları filolarına çeşitli kiralama yöntemleriyle veya satın alma yoluyla dahil ederler. Bu çalışmada hava yolu şirketinin uçağı satın alacağı varsayılmıştır. Fiyat kriteri bu çalışmada uçak üreticileri tarafından yayınlanan liste fiyatları üzerinden belirlenmiştir ve herhangi bir indirim oranı hesaba katılmamıştır.

Doğrudan İşletme Giderleri

Bir uçağın işletilmesi ile ilgili bütün giderleri kapsayan DİG, hava yolunun karlılığında büyük öneme sahiptir. ICAO (2017a) DİG'i ekip, yakıt, bakım-onarım ve sahip olma maliyetleri olmak üzere dörde ayırır. Bir hava yolundan diğerine değişebilen DİG, bu çalışmada Avrupa Hava Yolları Birliği'nin (AEA, 1987) yöntemi ile hesaplanmıştır.

Teknik Özellikler

Teknik özellikler ana kriteri uçak menzili, yolcu kapasitesi, kargo kapasitesi ve güvenilirlik gibi operasyonel kriterlerden oluşur. Bu kriter hava yollarının günlük işleyişiyle ilgili kararlarını ve uzun vadeli, stratejik kararlarını etkileyen uçak özelliklerini temsil eder. Ekonomik faktörler bir yana ayrılırsa, teknik özellikler bir uçağın bir uçuş noktasına nasıl (doğrudan veya aktarmalı) ve ne sıklıkla uçabileceğini belirler.

Uçuç Menzili

Uçuş menzili bir uçağın kalkış noktasından bir varış noktasına uçabileceği en uzun mesafedir. Bir uçağın menzili uçağın taşıdığı yolcu sayısı, kargo yükü ve yakıt miktarına göre değişebilir. Bu çalışmada uçuş menzili uçakların taşıyabileceği en fazla yolcu ile uçabilecekleri en uzun mesafe olarak kabul edilmiştir.

Yolcu Kapasitesi

Yolcu kapasitesi hava yollarının gelirlerini doğrudan etkilediğinden uçak seçiminde önemli bir yere sahiptir. Taşınabilecek yolcu sayısı güvenlik, menzil, kargo kapasitesi, kabin tasarımı gibi faktörlere bağlıdır. Hava yolu sektöründe genellikle iki veya üç sınıflı kabinler tercih edilmektedir. Bu çalışmada uçaklar iki sınıflı kabinler ile taşıyabileceği yolcu sayısı üzerinden karşılaştırılmışlardır.

Kargo Kapasitesi

Hava kargo, uçakların kargo bölümlerinde taşınan yük, bagaj ve postayı kapsamaktadır. Boeing (2021a), dünya üzerinde taşınan yüklerin değer bakımından %35'inin hava kargo olduğunu belirtmiştir. Taşınan toplam hava kargonun %44'ü ise yolcu uçaklarının kargo bölümlerinde taşınmıştır (IATA, 2020). Önümüzdeki 20 yılda hava kargo pazarının ortalama %4 büyüyeceği tahmini (Boeing, 2021a) de hesaba katıldığında kargo kapasitesi, yolcu uçağı seçimi sürecine dahil edilebilecek bir kriter olarak ortaya çıkmaktadır. Bu çalışmada kargo kapasitesi uçakların taşıyabileceği LD3 kargo konteyneri sayısıyla ölçülmüştür.

Güvenilirlik

Bir uçağın emniyetli bir biçimde operasyonuna devam edebilmesi için uçağın gövdesinin, motorlarının ve sistemlerinin güvenilir olması gerekir. Bu çalışmada uçak güvenilirliğinin ölçülmesi için uçağın gövde, motor ve sistem güvenilirliği ile yakından bağlantılı olan ETOPS (Extended Range Twin-engine Operations Performance Standards) derecesi kullanılmıştır. ETOPS derecesi, çift motorlu uçakların acil bir durumda tek motor seyir hızıyla bir yedek meydandan uzak olabileceği en uzun süreyi belirler. Uçağın ETOPS derecesi hava yolunun uçuş rotası planlamalarını da etkiler.

ETOPS belgelendirmesi için uçak sistemlerinin ve motorlarının yüksek güvenilirliğe sahip olması ve hava yolu şirketinin belirli yeterlilik ve uygulamalara sahip olması gerekmektedir (ICAO, 2014). Örneğin ETOPS-180 derecesi için çift motorlu bir uçağın uçuş sırasında 1.000 saatte 0,01'den az motor kapanma istatistiğine sahip olması gerekir (ICAO, 2014). Bazı hava yolu şirketleri, uçuşları ETOPS derecesi gerektirmemesine rağmen uçak güvenilirliğini ve performansını artırması için ETOPS bakım programları uygulamaktadır (Boeing, 1999).

Çevresel Etki

Uçakların yol açtığı çevresel etkiye düzenleyici kuruluşlar, hava yolu şirketleri, uçak üreticileri ve kullanıcılar tarafından büyük önem verilmektedir. Hava yolu endüstrisinde uzun yıllardır uçakların yol açtığı çevresel etkiyi azaltmak için çalışmalar yapılmaktadır. Uçak motoru teknolojisindeki gelişmeler ve bazı operasyonel uygulamalar sayesinde sürekli olarak iyileştirmeler sağlanmaktadır. Bu çalışmada uçakların yol açtığı CO_2 salınımı ve gürültü kirliliği çevresel etki kriteri altında gruplandırılmıştır.

CO_2 Salınımı

CO_2'nin de aralarında bulunduğu sera gazlarının küresel ısınmaya yol açtığı bilinmektedir. Havacılık endüstrisinin toplam CO_2 salınımındaki payı %2'dir (Lund ve diğerleri, 2017). IATA 2009'da havacılık endüstrisinin yol açtığı CO_2 salınımını düşürmek için kısa ve uzun vadeli hedefler belirlemiştir (IATA, 2019). Bu doğrultuda hava yolu şirketleri yakıt maliyetlerini ve uçakların yol açtığı çevresel etkileri azaltmak amacıyla yakıt tüketimi daha az olan yeni nesil uçakları tercih etmektedirler.

Gürültü Seviyesi

Uçak motorları ve uçak gövdesi etrafındaki hava akımından kaynaklanan gürültü, insanlar ve doğal hayat üzerinde olumsuz etkilere sahiptir. Çalışmalar, uçak kaynaklı gürültünün, insanlarda stres, hipertansiyon (Black ve diğerleri, 2007), uyku eksikliği, yorgunluk ve baş ağrısı (Franssen ve diğerleri, 2004) gibi çeşitli sağlık sorunlarına yol açtığını göstermişlerdir. Özellikle havalimanı çevresinde yaşayan insanlar uçağın kalkış, yaklaşma ve iniş safhalarındaki gürültüsüne daha çok maruz kaldığından bu sağlık sorunlarına karşı daha savunmasızlardır.

ICAO, uçak gürültüsünü yönetebilmek amacıyla standartlar ve tavsiye edilen uygulamalar ortaya koymuştur. Buna göre, uçak gürültüsü havalimanı çevresinde üç farklı noktada ölçülür ve standartlara uygunluğu denetlenir (ICAO, 2017b). Farklı ölçüm noktalarından elde edilmiş olan gürültü seviyesi verileri belirlenmiş olan limitten çıkarılır ve bu işlem sonucu elde edilen gürültü seviyesi verileri toplanır. Bu çalışmada, uçakların gürültü seviyeleri bu toplam üzerinden karşılaştırılmıştır.

Yolcu Konforu

Yolcuların bilet satın alırken önem verdiği konulardan birisi konfordur. Koltuklar arası mesafe, koltuk genişliği, kabin genişliği ve baş üstü dolapları yolcu konforunun temel bileşenleridir. Bunlar dışında yolcuların oksijen satürasyonu seviyesini etkileyen kabin irtifası da konforu etkileyen faktörlerden birisidir.

Kabin Hacmi / Koltuk

Bu çalışmada, yukarıda yolcu konforu ile ilgili bahsedilen bileşenlerin tek tek karşılaştırılması kriter sayısını artıracağından koltuk başına düşen kabin hacmi verileri kullanılmıştır. Bu şekilde yolcu başına düşen alanı ve yolcu konforunu karşılaştırma imkânı sağlanmıştır. Bu veri, toplam kabin hacminin koltuk sayısına bölünmesi ile bulunur.

Kabin İrtifası

Kabin içerisindeki basınç seviyesine denk gelen irtifa kabin irtifası olarak adlandırılır. Yolcu ve uçuş ekibinin yüksek irtifalarda uçan uçaklarda rahat nefes alabilmesi için uçak kabinleri en yüksek 8.000 ft irtifaya denk gelecek şekilde basınçlandırılırlar. Muhm ve diğerleri (2007) yaptıkları çalışmada 7.000 ve 8.000 ft arasındaki kabin irtifalarının 3 ila 9 saat uçuştan sonra yolcularda rahatsızlığa yol açtığını belirtmişlerdir. Boeing ve Oklahoma Eyalet Üniversitesi’nin ortak çalışması, 6.000 ft kabin irtifasının yolcularda daha az ağrıya ve yorgunluğa neden olduğunu ortaya koymuştur (Boeing, 2004). Yolcu konforu ile doğrudan bağlantılı olan kabin irtifası, ilk kez bu tezde uçak seçim kriteri olarak dahil edilmiştir.

Alternatif Uçaklar

Bu çalışmada geçtiğimiz on yılda hizmete girmiş ve en çok sipariş sayısına sahip olan dört geniş gövdeli yolcu uçağı alternatif olarak belirlenmiştir. Bunlar: Boeing 787-8, Boeing 787-9, Airbus A330-900 ve Airbus A350-900'dür. Bu uçaklar bir önceki nesil uçaklara göre daha düşük yakıt tüketimi, daha düşük gürültü seviyesi ve daha yüksek güvenilirlik gibi avantajlara sahiptirler.

Veri Toplama

Çalışmada kullanılan kriterlerin ağırlıklarının belirlenmesi amacıyla havacılık sektöründe filo planlama, uçak satın alma ve hava taşımacılığı ekonomisi gibi alanlarda tecrübe sahibi üç uzmana AHS ve DEMATEL yöntemlerinin uygulamasını içeren anketler uygulanmıştır.

AHS yönteminde ayrı ayrı alınan uzman görüşlerinin birleştirilebilmesi için Aczél ve Saaty (1983) ve Saaty (2008)'in de önerdiği üzere geometrik ortalama metodu kullanılmıştır. Birleştirilmiş İKM'lerin tutarlılık oranları ana kriterler ve teknik özellikler alt kriterleri için sırasıyla 0,036 ve 0,020 olarak hesaplanmış ve bu değerler 0,10 değerinin altında olduğu için birleştirilmiş İKM'ler tutarlı sayılmıştır. Diğer ana kriterlerin İKM'leri ikişer alt kriter içerdikleri için tamamen tutarlı kabul edilmişlerdir.

DEMATEL yönteminin uygulamasında uzmanların kriterleri ikili olarak karşılaştırması sonucu üç farklı DEM oluşturulmuştur. Bunların birleştirilebilmesi için Sara ve diğerleri (2015), Wang ve diğerleri (2012) ve Wu (2008) çalışmalarında da olduğu gibi aritmetik ortalama yöntemi kullanılmıştır.

BULGULAR

AHS Yöntemi Sonuçları

AHS yöntemi ile elde edilen veriler kullanılarak ana kriterlerin ağırlıkları ve alt kriterlerin yerel ağırlıkları belirlenmiştir. Buna göre ana kriterler olan ekonomik özellikler, teknik özellikler, çevresel etki ve yolcu konforunun ağırlıkları sırasıyla 0,4870, 0,3145, 0,1055 ve 0,0930 olarak hesaplanmıştır. Bu sonuçlara bakıldığında ekonomik özellikler ve teknik özelliklerin çevresel etki ve yolcu konforu kriterlerine kıyasla çok daha büyük öneme sahip olduğu görülmektedir. Uçak fiyatı ve DİG'in hava yollarının finansal durumu üzerindeki etkisi göz önünde bulundurulduğunda ekonomik özellikler kriterinin birinci sırada bulunması anlaşılır bir durumdur.

Alt kriterlerin ağırlıkları AHS yönteminde belirtildiği gibi hesaplanmıştır. Hesaplanan ağırlıklar incelendiğinde en önemli üç kriter sırasıyla DİG (0,3289), güvenilirlik (0,1658) ve fiyat (0,1581) olmuştur. Birkaç gider kaleminin birleşimi olan DİG, hava yollarının toplam giderlerinin yaklaşık %50'sini oluşturduğundan (Belobaba ve diğerleri, 2016) bu kritere atfedilen ağırlık yerindedir. AHS sonuçlarında ikinci sırada bulunan güvenilirlik, uçağın operasyona hazır bulunma durumunu etkilediğinden uçağın gelir getirme yeteneği ile de ilgilidir. Bu durum da bu kriterin sahip olduğu yüksek önemi açıklamaktadır. Bunun yanı sıra, fiyat kriteri beklendiği gibi uzmanlar tarafından en çok önem verilen kriterlerden biri olmuştur.

AHS yöntemi sonuçlarında kabin irtifası (0,0381), kargo kapasitesi (0,0258) ve gürültü seviyesi (0,0226) son üç sırada yer almışlardır. Önümüzdeki 20 yılda hava kargo alanında ortalama %4'lük bir büyüme beklenmektedir (Boeing, 2021a). Ancak Boeing (2020)'e göre yolcu uçaklarının varış noktalarının hepsinde yüksek kargo talebi bulunmayabilir ve dağıtım zamanları uçuş saatleri ile eşleşmeyebilir. Bu nedenlerden dolayı kargo kapasitesinin yolcu uçağı seçiminde göreceli olarak düşük bir değer elde etmesi anlaşılabilirdir. Uçuş menzili kriteri 0,0424 ile beklentinin altında bir ağırlık değeri elde etmiştir. Hava yollarının uçuş ağı planlamalarını etkileyen faktörlerden biri olan uçuş menziline atfedilen ağırlık bir hava yolundan diğerine şirketlerin farklı iş modellerine bağlı olarak değişebilir.

DEMATEL Yöntemi Sonuçları

Kriterlerin ağırlıkları ve EİH'ler DEMATEL yöntemi uygulanarak elde edilmiştir. EİH'lerde 0,3840 ve 0,2482 eşik değerleri kullanılarak güçlü etki ve orta derecede güçlü etkiler gösterilmiştir.

TİM incelendiğinde DİG'in fiyat ile birlikte en çok etkileşime sahip olan kriter olduğu görülmüştür. Bununla ilişkili olarak DİG ve fiyat, 0,1416 ve 0,1337 ağırlık değerleriyle ilk iki sırada yer almışlardır. Ayrıca, DİG ve fiyat arasında beklendiği gibi güçlü bir etki tespit edilmiştir. EİH incelendiğinde maksimum kalkış ağırlığı ile ilintili olan uçuş menzili, yolcu kapasitesi ve kargo kapasitesi kriterlerinin DİG ile etkileşimde olduğu görülmüştür. DİG’in uçak büyüklüğüne bağlı olduğu düşünüldüğünde bu bulgu anlaşılabilirdir. EİH, DİG’in güvenilirlik ile güçlü bir etkileşimi olduğunu da göstermektedir. Bu da güvenilirliğin bakım ile ilişkili olmasına bağlanabilir.

Fiyat kriteri yolcu kapasitesi ile güçlü bir etkileşime sahiptir. İki kritere ait veriler arasındaki korelasyonun pozitif ve değerinin 0,9689 olması bu bulguyu destekler niteliktedir. EİH genel olarak incelendiğinde fiyat kriteri beklendiği gibi teknik özellik kriterlerinin hepsi ile etkileşime sahiptir. Fiyatın ayrıca çevresel etki kriterleri üzerinde etkisi bulunmaktadır. Bu durum araştırma ve geliştirme giderlerinin bu kriterler üzerindeki dolaylı etkisi ile açıklanabilir.

EİH’ler incelendiğinde en az etkileşime sahip olan kriterlerin sırasıyla kabin hacmi / koltuk (0,0769), gürültü seviyesi (0,0715) ve kabin irtifası (0,0225) olduğu görülmüştür. Bununla bağlantılı olarak bu kriterler DEMATEL yöntemindeki en düşük ağırlıkları elde etmişlerdir.

AHS-TOPSIS ve DEMATEL-TOPSIS Yaklaşımlarının Sonuçları

Çalışmanın son adımında AHS ve DEMATEL yöntemleri ile elde edilen iki farklı kriter ağırlığı seti TOPSIS yöntemi ile birlikte kullanılarak en iyi geniş gövdeli yolcu uçağı seçimi için iki farklı sonuç belirlenmiştir. TOPSIS yönteminin uygulamasında pozitif ve negatif ideal çözümleri hesaplamak için uçuş menzili, yolcu kapasitesi, kargo kapasitesi, güvenilirlik ve kabin hacmi / koltuk fayda kriterleri olarak belirlenirken, fiyat, DİG, CO_2 salınımı, gürültü seviyesi ve kabin irtifası maliyet kriterleri olarak belirlenmiştir.

AHS-TOPSIS yaklaşımında alternatiflerin pozitif ideal çözüme olan bağıl yakınlıkları hesaplanmış ve sıralama sonucunda en iyi geniş gövdeli yolcu uçağı 0,7357 değeri ile Boeing 787-8 olarak belirlenmiştir. Boeing 787-9, Airbus A350-900 ve Airbus A330-900 sırasıyla 0,4495, 0,4194 ve 0,2397 değerlerini elde etmişlerdir. Boeing 787-8, diğer alternatiflere kıyasla daha az kapasite sunmasına rağmen daha düşük bir liste fiyatına ve DİG’e sahiptir.

DEMATEL-TOPSIS yaklaşımında ilk üç alternatiflerin sıralamaları değişmiştir. Bu yaklaşımın sonucunda alternatifler arasından Airbus A350-900, 0,6744 bağıl yakınlık değeri ile en iyi geniş gövdeli yolcu uçağı olarak belirlenmiştir. Boeing 787-8, Boeing 787-9 ve Airbus A330-900’un bağıl yakınlık değerleri sırasıyla 0,6429, 0,6216 ve 0,2912 olarak hesaplanmıştır.

Sonuçlar karşılaştırıldığında Airbus A330-900’un iki yaklaşımda da sonuncu sırada olduğu görülmüştür. Bu sonuç, Airbus A330-900’un toplam sipariş sayısının alternatifler arasında en düşük olması ile tutarlıdır. Yaklaşımlar arasındaki sıralama farklılıklarının nedeni, AHS yönteminde kriterler arası bağımsızlık varsayımının yapılması olarak değerlendirilebilir.

SONUÇ

Bu çalışmada hava yolu şirketlerinin geniş gövdeli yolcu uçağı seçim problemi ÇKKV yöntemleri ile incelenmiştir. Toplamda dört ana kriter ve on alt kriter kullanılan çalışmada kriter ağırlıkları AHS ve DEMATEL yöntemleri ile elde edilmiş, sonrasında bu yöntemler TOPSIS yöntemi ile birleştirilerek en iyi alternatif belirlenmiştir. DEMATEL-TOPSIS sonuçları, AHS-TOPSIS sonuçları ile karşılaştırılmış ve kriter bağımsızlığı varsayımının sonuçlar üzerindeki etkisi incelenmiştir. Ayrıca, DEMATEL yöntemi kullanılarak EİH’leri oluşturulmuş ve uçak seçimi kriterlerinin birbirleri arasındaki etkileşimler belirlenmiştir.

Çalışma farazi bir hava yolu firması için olduğundan uçak seçim sürecinde etkiye sahip olabilecek olan filo benzerliği ve teslimat süresi kriterleri çalışmaya dahil edilmemiştir. Çalışmanın bir diğer sınırlaması da COVID-19 salgını nedeniyle uzmanlarla yüz yüze görüşme imkanının kısıtlı olmasıdır.

Bu tez uçak seçim problemine hava yolu bakış açısıyla yaklaşmış olmasına rağmen kriterler arası etkileşimler ve kriterlere atfedilen önem dereceleri gibi bulgular uçak üreticileri açısından da yararlı olabilir. Ayrıca, tezde kullanılan yaklaşımlar hava yolları tarafından filodan ayrılacak uçakların seçiminde de kullanılabilir.

Çalışmada kullanılan yaklaşımlar gelecekte uygun kriterler kullanılarak dar gövdeli yolcu uçağı, kargo uçağı ve bölgesel yolcu uçağı seçimi problemlerinde kullanılabilir. Bunun yanı sıra, bu çalışmanın geçerliliği başka bir ÇKKV yöntemi kullanılarak da incelenebilir.

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