공학석사학위논문

Aircraft operations under the EU's sustainable aviation fuel policy

지속가능한 항공 연료 도입을 고려한 항공기 운영 방식 결정

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Abstract

Aircraft operations under the EU's sustainable aviation fuel policy

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This study proposes aircraft operation strategies to airlines by exploring fleet assignment and aircraft re-routing problems by code-share under the EU' s carbon control programs. The research was motivated by the introduction and related policies of sustainable aviation fuel (SAF) and the EU emissions trading system (EU-ETS) with it. Airlines are divided into two types by their characteristics, and mixed-integer linear programming was developed respectively. The airlines get additional profit from this model, and various managerial insights are suggested.

Keywords: Sustainable aviation fuel (SAF), Emissions trading system, Carbon credit, Fleet assignment, Aircraft re-routing, Code-share

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Chapter 1

Introduction

The Kyoto Protocol, a climate agreement, expired in 2020, and the agreement to discuss the following climate policy took place in Paris in 2015. The Paris Agreement expanded the Kyoto Protocol, which proposed emissions reduction targets concentrated on advanced countries to allocate carbon reduction obligations to 195 countries. Accordingly, the countries should set their own targets for carbon emissions and comply with them. Most countries are introducing various policies to meet their reduction targets, designating an upper limit of carbon emissions for each industry and making the companies trade insufficient or remaining emissions credits in the market. The most noteworthy policy on carbon emissions is the EU-ETS, the European Union' s carbon trading system. The EU-ETS was introduced on a trial basis in 2005, during phase one of the Kyoto Protocol, and is now known as the world' s most successful carbon trading system. The aviation industry was not initially subject to EU-ETS but has been included since 2012 because the aviation sector took about 12 percent of the total carbon emissions in the transportation sector, and the proportion was predicted to increase. In other words, airlines are no longer free from carbon emissions. Airlines will be assigned carbon credits that can be emitted by the relevant institutions. If they emit more carbon than the number of carbon credits allocated, they must buy the insufficient amount.

To this end, various methods are being sought to reduce carbon emissions in the aviation sector, and the most promising method is sustainable aviation fuel (SAF). SAF is an eco-friendly aviation fuel produced in various ways. Although it falls into a relatively high price range like most eco-friendly fuels, it has the advantage of reducing carbon emissions by up to 80 percent compared with traditional aviation fuel (TAF). In addition, SAF can be used by fueling existing aircraft without any additional equipment or installation, and it has the characteristically named "drop-in-fuel," which means that it can be used freely by blending with TAF. Unlike other technologies, such as electrified and hydrogen airplanes, which are expensive to introduce and come with various potential risks, this characteristic of SAF allows airlines to increase the proportion of SAF blended with TAF gradually. In other words, the drop-in fuel characteristic lowers the barrier to entry for airlines to introduce SAF. It can also play a role as a stepping stone for future transitions to technologies that require more significant investment and risks. The EU is very active in promoting the SAF. According to the recently announced ReFuelEU policy of the EU' s "fit for 55" package, all fuels supplied within the EU must contain at least 2 percent of SAF from 2025, and the proportion will gradually increase to 5 percent in 2030, 20 percent in 2035, and 63 percent in 2050.

Policies and regulations to increase SAF usage continue to be discussed. However, it is challenging to commercialize SAF rapidly, as it falls into a relatively high price range, similar to most eco-friendly fuels. This is because it is difficult to be competitive in price compared with the existing TAF. For this reason, related organizations are introducing various assistance policies to increase the use of SAF.

Typical assistance methods are a tax for using TAF or subsidizing the use of SAF. [28] claimed that in the situation of SAF introduction, introducing the carbon credit system as assistance increases the rate at which SAF replaces TAF and brings additional welfare. Similarly, this study considers the situation in which EU-ETS, the European Union' s emissions trading system, exists with SAF policy as one of the ways to promote SAF' s market activation. However, carbon regulations generally act in the direction of worsening airline profitability. This is because if airlines emit the same amount of carbon as before, they will pay the penalty, so additional efforts are needed to prevent this, such as using high-priced SAF or developing eco-friendly technologies. Therefore, airlines use various strategies to minimize the profit decline as carbon regulations become tight.

This study explores a strategy for using the fleet assignment and code-share agreement. Fleet assignment is a problem of assigning various types of aircraft to predetermined flight legs. Most airlines have several types of aircraft. Due to the various characteristics of each aircraft type, such as different fuel efficiency, passenger capacity, and available distance, just assigning these aircraft to appropriate flight legs can significantly increase the airline' s profit. In particular, in the current situation in which carbon regulations are gradually intensifying, it is believed that the fleet assignment, which reflects the difference between areas where carbon regulations are applied and areas where carbon regulations are not applied, will have more utility than before. Code-share is a system that allows airlines to sell tickets for flights that do not operate by themselves through agreements with other airlines. So the agreements include airlines that operate actual flight legs and airlines that only sell tickets through marketing. Through this method, airlines can procure routes to areas where it is difficult to operate, owing to low demand or long distances, and can gain various benefits, such as increasing the frequency of flight legs without increasing the number of aircraft. Currently, the EU' s SAF mandate policy only targets aircraft departing or arriving from the EU territory. So, if airlines operating long-haul routes from outside Europe to Europe have code-share agreements with airlines operating multiple short-haul routes inside Europe, the damage to carbon regulations will be minimized. Therefore, in this study, the analysis will be conducted by dividing airlines into two types: inside Europe and outside Europe.

The remainder of this study is organized as follows: Chapter 2 examines existing studies through a literature review and defines the contribution of this study. Chapter 3 describes the problem situation of this study and presents two mathematical models that reflect the situation. Chapter 4 performs numerical experiments of the two models presented in Chapter 3, and based on this, it provides strategies and managerial insights that airlines can use in the decision-making process. Finally, Chapter 5 summarizes and organizes the contents so far and proposes the limitations of this study and further research.

Chapter 2

Literature review

Researches to manage carbon emissions from the transportation sector have been conducted extensively. [19] proposed a multi-proxy allocation system including demand and supply indicators to geographically allocate carbon emissions from transportation and explore the fine scale. [12] developed a modeling framework that integrates Florida' s air pollution with agent-based activity and travel simulations, characterizing exposure and exposure inequality to traffic-related air pollution. [20] developed a static spatial simulation for daily travel behavior and conducted a case study on Beijing, which estimated the carbon emissions of Beijing transportation at the disaggregate level. In particular, since the aviation sector was included as a carbon emission management industry by the European Union in 2012, various studies have been conducted to manage carbon emissions in the aviation industry. For example, based on the fact that flights in less accessible areas have high carbon emissions per distance, [8] developed a framework that simultaneously performs minimization of emissions and maximization of airport accessibility. Mixed-integer linear programming was established, and experiments were conducted using data from United Airlines. Furthermore, Many studies on SAF have recently received significant attention.

Several SAF-related studies have been conducted until now, but most studies focus on production and supply aspects rather than on using SAF. [27] explored the method of producing SAF with a boiling point similar to that of existing aviation fuels by transforming microalgae oil. [22] studied the problem of SAF production using a specific crop called ”carinata”. Mixed integrator linear programming was used to optimize the entire supply chain from farm to airport to derive the required facilities. [9] studied how to produce SAF by mixing various materials. The study aimed to improve fuel performance, reduce emissions at a minimum cost, and create a four-dimensional Pareto front across potential solutions.

Regarding the use of SAF, policy analysis to increase SAF consumption and revitalize the market and expert interview analysis to obtain related insights are the mainstream. [4] evaluated two policy scenarios related to SAF from the perspective of SAF consumption and emissions amounts. Life-cycle assessment and Monte Carlo simulation were used, and the possibility of reducing greenhouse gas emissions by 37.5 to 50 percent by 2050 was found to be 3.5 percent. [14] compared the policy objectives of the two policies, carbon tax, and SAF quota, in terms of emission and social welfare. With the emissions-oriented policy, the higher the emissions target, the more the SAF quota was met than with the carbon tax policy. With the social welfare-oriented policy, if the SAF price was sufficiently low, the SAF quota showed a relatively small emissions level. [6] interviewed 36 senior executives for the successful introduction of the SAF, which is suffering from deadlock during commercialization. Through this, they found a sector in which free-riding was occurring and found that the problem was insufficient investment and lack of responsibility. [1] studied the ways to revitalize the stagnant SAF market through interview analysis, like [6].

While existing interviews use a cognitive mapping approach, this study investigated the SAF development process by developing a multi-layer cognitive map.

There are not many studies that quantitatively analyzed the use of SAF by establishing a mathematical model, but it has been conducted as follows. [13] solved the air traffic flow management (ATFM) problem that considers delay and re-routing costs under the SAF policy. The Bi-objective optimization model was used, and the Pareto solution using k-means clustering was derived. [25] studied how airlines respond to the EU' s SAF mandate policy using fuel tankering. The possibility of fuel tankering weakening the effectiveness of the SAF mandate was explored. However, as far as we know, few studies have been conducted that have introduced SAF into the fleet assignment problem like this study.

The fleet assignment problem is an area that has long been studied in the aviation sector, and there are many related studies. The fleet assignment problem can be divided into two categories: a simple fleet assignment problem that deals with only aircraft allocation problems in consideration of stochastic situations or robustness, and an integrated fleet assignment problem that considers former decision-making steps in aviation studies, such as flight scheduling problems or later decision-making steps like crew scheduling problems. Recent major studies related to simple fleet assignment problems are as follows. [21] solved the fleet assignment problem under carbon emissions reduction in consideration of random demand, fair price, and avgas price. the multi-criteria method was used to minimize emissions costs and maximize profit simultaneously. [26] deal with the problem of fleet assignment, which additionally considers aircraft fuel efficiency and carbon emissions costs related to cruise speed. They used mixed-integer second-order cone programming and developed a two-stage algorithm to solve the large-size problem within a reasonable time. As a result of a numerical experiment on a major US airline, it was confirmed that the operational cost decreased by 20 percent compared with the existing schedule presented by the airline.

Recent major studies related to integrated fleet assignment problems are as follows. [15] conducted a study on integrated fleet assignment with scheduling of regional scales using electrified air mobility. The authors of this study claimed that converting currently used aircraft to electrified air mobility can cover twice the area currently in service. [11] studied an integrated fleet assignment problem that simultaneously considers airline scheduling, fleet assignment, and routing problems by introducing cruise control. Non-linear mixed-integer programming was handled by second-order conic reformulation, and a heuristic was proposed for the large-size problem. [16] studied the integrated problem considering scheduling and fleet assignment. Two-stage stochastic programming was used to consider stochastic demand and fare. [2] established an integrated model that considers fleet assignment, routing, and crew pairing at the same time. Mixed-integer programming was developed on a very large scale, and a metaheuristic consisting of a decomposition approach and a proximity search algorithm was applied. [17] address the problem of aircraft reassignment and flight route adjustment in EU-ETS situations. This study uses a mathematical model and develops a genetic algorithm (GA) that quickly handles the proposed model to solve the large-size problem. [7] determined the fleet size of one type of aircraft and solved the fleet assignment problem. The validity of the proposed metaheuristic approach was proved by comparing the result of solving the same model with CPLEX. Recently, in the area of fleet assignment, studies have been mainly conducted to propose a complex integrated fleet assignment model that considers multiple decision-making steps simultaneously. In this study, ETS and SAF policies are introduced into a simple fleet assignment model.

The fields related to EU-ETS, the European Union' s emissions trading system, have also been studied extensively. In particular, as the aviation industry has been included in the carbon emissions management industry since 2012, several studies have been conducted dealing with EU-ETS in the aviation field. [29] studied the effect of carbon permits (CP) in the presence of competition in cap-and-trade and green strategies situations. This model reflects consumers' perceptions of eco-friendly transportation as an airline response function through the lens of how airlines respond to CP by pricing and investment. [24] analyzed the impact of EU-ETS by expanding existing studies. Efforts to reduce airline costs were explicitly reflected, and in particular, the impact of reduction strategies, firm action in the secondary market, free quotas, and fines were considered together. This provided insights to support policy-making decisions and found that there was a trade-off between free quotas and efficiency costs. [23] identified the direct cost relationship between the aviation sector and the EU-ETS through a case study. Scenario analysis was conducted by dividing emissions permit prices into three types: low-, medium-, and high-bound, and an economic model was established to analyze the impact of costs on airfare, revenue, and social cost. [5] propose a carbon emissions allocation method determining the free carbon quota for airlines under the EU-ETS. To overcome the limitation that the existing allocation method does not consider airlines that use efficient aircraft, the problem situation, including the use of efficient aircraft, was tested and verified using the Cournot model. However, to our knowledge, few studies have so far applied EU-ETS to the fleet assignment problem by combining it with the SAF policy.

Several studies related to airline code-share arrangements have also been conducted, but most of them are focused on the contract between airlines or the field of selecting flight legs suitable for code-share. [18] conducted a study to select flight as the code-share subject. Most existing code-share studies did not consider the change in demand due to code-share. This study considered changes in passenger demand and reflected the interaction between code-share flights. The authors of the study express this as a mathematical model and propose two heuristics that can solve the proposed mathematical model. [3] analyze how the price strategy of European airline carriers was influenced by international code-share. It was found that code-share particularly increases the fare of early bookers, and in the process, marketing carriers offer higher prices. [10] explored the general process of code-share contracts and quantified it based on Lufthansa' s empirical data. As a result, it was discovered that selfishness, information asymmetry, and system decentralization must be overcome for effective code-share operation. [30] studied the impact of domestic code-share on airlines' on-time performance (OTP) in the US aviation industry. Through this angle, the author argued that most domestic code-share belongs to virtual code-share, and the code-share route has a relationship with less arrival delay. However, as far as we know, few studies have interpreted code-share agreements from an environmental point of view. In particular, very few studies propose code-share agreements to reduce environmental regulations' impact on airlines.

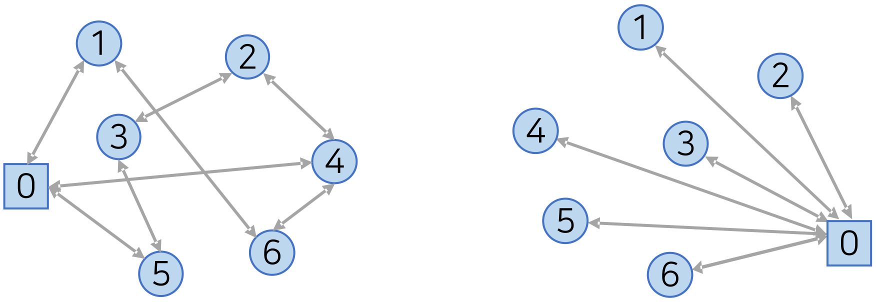
Chapter 3

Mathematical formulation

3.1 Problem description

In this study, we explore the best fleet assignment strategies and re-routing strategies by code-share that airlines can take under the carbon policies of the EU. The study mainly focuses on using SAF and introducing related regulations, which have recently increased in importance. There are two airlines in this study that have different characteristics. The first type of airline is located in Europe. Unlike most airlines not located in Europe, a Type 1 airline has the fifth freedom outlined in the Open Skies Agreement. The Open Skies Agreement is an inter-country agreement that limits the types of routes airlines can operate, which allows some airlines in Europe to operate routes between other countries or third countries, as well as routes connecting the country where the airline headquarters are located with another country. That is why European airlines Ryanair and EasyJet can fly to all European countries like a net. Because a Type 1 airline is located in Europe, it operates international flight legs among European countries and neighboring countries with agreements, as if they were domestic flights. In addition, the airline is directly affected by the carbon policies of the EU and has a high frequency of short-haul flight legs that operates several times a day.

A Type 2 airline is located outside of Europe. A Type 2 airline has the fourth freedom outlined in the Open Skies Agreement, which allows only direct routes connecting the country where the airline headquarters are located with other countries. Airlines such as Type 2 may open and operate additional routes between third countries through contracts with other countries or airlines, but such cases are relatively very few, so this study does not cover this option. Since the airline is located outside Europe, routes unrelated to Europe are not directly affected by the carbon policies of the EU. In addition, the Type 2 airline has the condition of low-frequency, flying various distances with flight legs that operate, at most, once a day to at least once a week. The difference in route structure between the Type 1 airline and the Type 2 airline is shown in Figure 3.1.



(a) Type 1 airline: inside Europe (b) Type 2 airline: outside Europe

Figure 3.1: Routes of the two airlines under the Open Skies Agreement

In this study, two mathematical models of the two types of airlines are developed. The decision maker of each model is the airline, which aims to maximize the total profit, which integrates the revenue, navigation cost, SAF mandate, penalty of carbon emissions, and carbon credits. In the case of the Type 1 airline, short-haul routes within the EU are operated several times, so the aircraft is assigned to the flight legs that are entangled, most efficiently by a small number of aircraft. So the time-space model that covers all the predetermined flight legs is based on Model 1. The time-space model only determines how to allocate fleets with the flight schedule fixed in advance. It sets the combination of time and place as one node to consider flight time and space simultaneously. The aircraft type is then assigned to flight legs and ground arcs passing through each node. In this study, the fleet assignment problem is expanded to include the EU' s SAF policy and the ETS. In addition, the SAF was introduced as an emissions reduction method for airlines, so variables that determine the SAF blending ratio for each flight leg are added to reflect this. Since SAF has a relatively high price range, this study introduced ETS as a means to increase SAF' s price competitiveness. In other words, a Type 1 airline assigns aircraft types to flight legs, as in a typical fleet assignment model, and determines the SAF blending proportion of aircraft-assigned flight legs. On top of that, the airline makes decisions on whether to sell the residual carbon credits without using them all or to offset the excess of the quota by purchasing additional carbon credits.

The Type 2 airline operates relatively long flight legs compared to the Type 1 airline. Unlike Model 1, which considers fleet assignment of complicated routes between countries several times a day, Model 2 does not consider fight times, because it deals with the problem of flights operating at least twice a week and at most once a day. Therefore, it is more important to decide what type of aircraft is allocated to a specific country and to change the route rather than the simple fleet assignment problem of assigning aircraft to fixed flight schedules. For this reason, Model 2 assumes that one aircraft operates only one route repeatedly, and re-routing is possible to separate one route into two stopover routes via code-share with another airline. In other words, Type 2 aircraft will make additional decisions about which flights to code-share in the decision-making of Type 1 aircraft.

3.2 Notations

The model sets and parameters are defined as follows:

Sets

$I:$ set of flight legs

$A:$ set of ground arcs

$N:$ set of nodes

$K:$ set of aircraft types

$I(n):$ set of legs arriving at the node n

$O(n):$ set of legs departing from the node n

$n^+:$ ground arc originating at node n

$n^-:$ ground arc terminating at node n

$CG:$ set of ground arcs that cross the count time

$CL:$ set of flight legs that cross the count time

Parameters

$q_i:$ SAF mandate quota of leg i

$l_s:$ SAF mandate violation penalty per unit

c_i^k : fixed operating cost when aircraft type k assigned on leg i

p^k : passenger capacity of aircraft type k

b^k : number of available aircraft type k

d_i : demand of leg i

t_i : fare price of leg i

$\tau_{ii'}$: fare price of code-share leg between the arrival of leg i and i'

p_t : traditional aviation fuel price

p_s : sustainable aviation fuel price

E_i^k : actual emission amount of leg i assigned to aircraft type k

α : proportion of total free allowance

β : demand change proportion due to code-share agreement

γ : revenue sharing proportion of code-share agreement

p_m : carbon price on the market

l_e : penalty applied to emission unit not covered by the allowances

g_i^k : fuel consumption amount of leg i assigned to aircraft type k

R_i^k : capacitated demand of leg i assigned to aircraft type k

Decision variables

f_i^k : 1 if plane k is assigned on leg $i, 0$ otherwise

y_a^k : number of aircraft of type k on the ground arc a

x_i^k : SAF blending proportion of type k assigned on leg i

s_i^k : 1 if plane k assigned on leg i violates the SAF mandate, 0 otherwise

z_i : 1 if leg i takes on code-share passengers, 0 otherwise

$a_{ii'}$: transferred demand of leg i to leg i'

$o_{ii'}$: actual number of passengers transferred in $a_{ii'}$

δ_n : number of allowances not returned by the airline

δ_v : number of allowances traded by the airline

E_{tf} : total free allowances for the airline

r_i^k : capacitated demand of leg i assigned to aircraft type k

3.3 The fleet assignment model under carbon policies (Model 1)

$$\begin{aligned}
\max \quad & \sum_i \sum_k t_i R_i^k f_i^k \\
& - \sum_i \sum_k (c_i^k f_i^k + g_i^k (p_t f_i^k + (p_s - p_t) x_i^k)) \\
& - \sum_i \sum_k l_s (s_i^k q_i - w_i^k) g_i^k + (p_m \delta_v - l_e \delta_n^+) && \text{(3.1)}
\end{aligned}$$

$$\text{s.t.} \quad \sum_k f_i^k = 1 \qquad \forall i \in I \quad \text{(3.2)}$$

$$y_{n+}^k + \sum_{i \in O(n)} f_i^k - y_{n-}^k - \sum_{i \in I(n)} f_i^k = 0 \qquad \forall n \in N, \forall k \in K \quad \text{(3.3)}$$

$$\sum_{a \in CG} y_a^k + \sum_{i \in CL} f_i^k \leq b^k \qquad \forall k \in K \quad \text{(3.4)}$$

$$x_i^k + G s_i^k + (1 - f_i^k) \geq q_i \qquad \forall i \in I, \forall k \in K \quad \text{(3.5)}$$

$$s_i^k \leq f_i^k \qquad \forall i \in I, \forall k \in K \quad \text{(3.6)}$$

$$x_i^k \leq f_i^k \qquad \forall i \in I, \forall k \in K \quad \text{(3.7)}$$

$$\delta_n = \sum_i \sum_k \left((f_i^k - x_i^k) E_i^k \right) - E_{tf} + \delta_v \quad \text{(3.8)}$$

$$E_{tf} = \alpha \sum_i \sum_k E_i^k f_i^k \quad \text{(3.9)}$$

$$w_i^k \leq s_i^k \qquad \forall i \in I, \forall k \in K \quad \text{(3.10)}$$

$$w_i^k \leq x_i^k \qquad \forall i \in I, \forall k \in K \quad \text{(3.11)}$$

$$w_i^k \geq x_i^k + (s_i^k - 1) \qquad \forall i \in I, \forall k \in K \quad \text{(3.12)}$$

$$w_i^k \geq 0 \qquad \forall i \in I, \forall k \in K \quad \text{(3.13)}$$

$$\delta_n^+ \geq 0 \qquad \forall n \in N \quad \text{(3.14)}$$

$$\delta_n^+ \geq \delta_n \qquad \forall n \in N \quad (3.15)$$

$$x_i^k \geq 0 \qquad \forall i \in I, \forall k \in K \quad (3.16)$$

$$y_a^k \geq 0 \qquad \forall a \in A, \forall k \in K \quad (3.17)$$

$$f_i^k \in \{0, 1\} \qquad \forall i \in I, \forall k \in K \quad (3.18)$$

$$s_i^k \in \{0, 1\} \qquad \forall i \in I, \forall k \in K \quad (3.19)$$

(3.1) is the objective function, which means the total profit of the airline in the presence of carbon emissions trading with the SAF mandate. The objective function is a value that takes into account revenue and carbon emissions trading, excluding navigation cost and SAF penalty costs. Constraint (3.2) means that only one type of aircraft should be assigned to one flight leg. Constraint (3.3) ensures that a particular aircraft type leaves and arrives at each airport in the same number. Constraint (3.4) limits the total number of aircraft types allocated to ground arcs and flight legs to be less than or equal to the number of aircraft held. Constraint (3.5) express that if the SAF proportion of the aircraft type k operating the leg i is less than the q_i, which is the quota of leg i, the s_i^k becomes 1. Constraints (3.6) and (3.7) are linking constraints that mean if type k is not assigned to leg i, SAF proportion and penalty variable must be zero. Constraint (3.8) is an equation related to carbon transactions, which represents the relationship between the airline' s total carbon emissions, free quotas, and carbon transactions. Constraint (3.9) determines the ratio of the free quota to the total carbon emissions. Constraints (3.10), (3.11), (3.12), and (3.13) are the linearized expression of $w_i^k = s_i^k x_i^k$. Constraints (3.14) and (3.15) are the linearized expression of $\delta_n^+ = max\{0, \delta_n\}$. Constraints (3.16), (3.17), (3.18), and (3.19) are constraints representing the characteristics of variables. In this case, R_i^k is the actual number of passengers of the type k aircraft operating leg i, and is determined to be the smaller of the demand d_i of leg i and the passenger capacity b^k of type k. In the case of l_e, the penalty for the airline to emit more than its free quota and carbon credits held, must be greater than the market price of the carbon credits, p_m. Otherwise, risk-free arbitrage may occur.

3.4 The fleet assignment and the aircraft re-routing model under carbon policies (Model 2)

$$\begin{aligned}
\max \quad & \sum_i \sum_k t_i v_i^k - \sum_i \sum_k (c_i^k f_i^k + g_i^k (p_t f_i^k + (p_s - p_t) x_i^k)) \\
& - \sum_i \sum_k l_s (s_i^k q_i - w_i^k) g_i^k + (p_m \delta_v - l_e \delta_n^+) \\
& + \sum_i \sum_{i'} \gamma \tau_{ii'} o_{ii'} && (3.20)
\end{aligned}$$

$$\text{s.t.} \quad \sum_k f_i^k \leq 1 \qquad \forall i \in I \quad (3.21)$$

$$\sum_i f_i^k \leq b^k \qquad \forall k \in K \quad (3.22)$$

$$x_i^k + G s_i^k + (1 - f_i^k) \geq q_i \qquad \forall i \in I, \forall k \in K \quad (3.23)$$

$$s_i^k \leq f_i^k \qquad \forall i \in I, \forall k \in K \quad (3.24)$$

$$x_i^k \leq f_i^k \qquad \forall i \in I, \forall k \in K \quad (3.25)$$

$$\delta_n = \sum_i \sum_k (f_i^k - x_i^k) E_i^k - E_{tf} + \delta_v \qquad (3.26)$$

$$E_{tf} = \alpha \sum_i \sum_k E_i^k f_i^k \qquad (3.27)$$

$$\beta \cdot d_i (1 - \sum_k f_i^k) = \sum_{i'} a_{ii'} \qquad \forall i \in I, \forall i' \in I \quad (3.28)$$

$$G \cdot \sum_k f_i^k \geq \sum_{i'} a_{i'i} \qquad \forall i \in I \quad (3.29)$$

$$r_i \leq d_i + \sum_{i'} a_{i'i} \qquad \forall i \in I, \forall i' \in I \quad (3.30)$$

$$r_i \leq \sum_k p^k f_i^k \qquad \forall i \in I \quad (3.31)$$

$$o_{ii'} \leq a_{ii'} \qquad \forall i \in I, \forall i' \in I \quad (3.32)$$

$$r_i - d_i \leq Gz_i \qquad \forall i \in I \tag{3.33}$$

$$r_i - d_i \geq G(z_i - 1) \qquad \forall i \in I \tag{3.34}$$

$$0 \leq \sum_{i'} o_{i'i} \qquad \forall i \in I, \forall i' \in I \tag{3.35}$$

$$\sum_{i'} o_{i'i} \leq r_i - d_i + G(1 - z_i) \qquad \forall i \in I, \forall i' \in I \tag{3.36}$$

$$r_i - d_i + G(z_i - 1) \leq \sum_{i'} o_{i'i} \qquad \forall i \in I, \forall i' \in I \tag{3.37}$$

$$\sum_{i'} o_{i'i} \leq Gz_i \qquad \forall i \in I, \forall i' \in I \tag{3.38}$$

$$w_i^k \leq s_i^k \qquad \forall i \in I, \forall k \in K \tag{3.39}$$

$$w_i^k \leq x_i^k \qquad \forall i \in I, \forall k \in K \tag{3.40}$$

$$w_i^k \geq x_i^k + s_i^{k-1} \qquad \forall i \in I, \forall k \in K \tag{3.41}$$

$$w_i^k \geq 0 \qquad \forall i \in I, \forall k \in K \tag{3.42}$$

$$v_i^k \leq r_i \qquad \forall i \in I, \forall k \in K \tag{3.43}$$

$$v_i^k \leq G \cdot f_i^k \qquad \forall i \in I, \forall k \in K \tag{3.44}$$

$$0 \leq v_i^k \qquad \forall i \in I, \forall k \in K \tag{3.45}$$

$$\delta_n^+ \geq 0 \qquad \forall n \in N \tag{3.46}$$

$$\delta_n^+ \geq \delta_n \qquad \forall n \in N \tag{3.47}$$

$$a_{ii} = 0 \qquad \forall i \in I \tag{3.48}$$

$$o_{ii} = 0 \qquad \forall i \in I \tag{3.49}$$

$$o_{ii'} \leq 0 \qquad \forall i \in I, \forall i' \in I \tag{3.50}$$

$$x_i^k \geq 0 \qquad \forall i \in I, \forall k \in K \tag{3.51}$$

$$f_i^k \in \{0, 1\} \qquad \forall i \in I, \forall k \in K \tag{3.52}$$

$$s_i^k \in \{0,1\} \qquad \forall i \in I, \forall k \in K \quad (3.53)$$

(3.20) is the objective function, which means the total profit of the airline in the presence of carbon emissions trading with the SAF mandate. The objective function is a value that takes into account revenue and carbon emissions trading, excluding navigation cost and SAF penalty costs, and adds additional revenue from code-share. Constraint (3.21) means that only one type of aircraft should be assigned to one flight leg. Constraint (3.22) limits the total number of aircraft types allocated to flight legs to be less than or equal to the number of aircraft held. The constraint formulas (3.23), (3.24), (3.25), (3.26), and (3.27) have the same meaning as constraints (3.5), (3.6), (3.7), (3.8), and (3.9) of Model 1. Constraint (3.28) means that the demand of the abolished flight legs multiplied by the demand reduction ratio β is transferred to the demand of the remaining flight legs. Constraint (3.29) means that when a particular flight leg is abolished, the route cannot cover the demand transferred from another legs. Constraints (3.30) and (3.31) are the linearized form of $r_i = min\{d_i + \sum_{i'} a_{i'i}, \sum_k p^k f_i^k\}$, which defines the number of passengers actually aboard on flight leg i. Constraint (3.32) states that the transferred number of passengers from the abolished leg i to leg i' must be less than or equal to the demand transferred from abolished leg i to leg i'. Constraints (3.33), (3.34), (3.35), (3.36), (3.37), and (3.38) are the linearized expressions representing the relationships among r_i, d_i, and $o_{i'i}$. Constraints (3.39), (3.40), (3.41), and (3.42) have the same meaning as constraints (3.10), (3.11), (3.12), and (3.13) of Model 1. Constraints (3.43), (3.44), and (3.45) are the linearized form of $v_i^k = r_i f_i^k$. Constraint (3.46) and (3.47) have the same meaning as constraints (3.14) and (3.15) of Model 1. Constraints (3.48) and (3.49) mean that they cannot cover the demand of themselves. Constraints (3.50), (3.51), (3.52), and (3.53) represent the characteristics of the variables.

Chapter 4

Numerical experiments

In this Chapter, numerical experiments are performed to help the airline' s decision-making process and to derive managerial insights through the models presented above. The experiments were conducted on Model 1 and Model 2, respectively, using the commercial software Xpress.

4.1 Experiments for Model 1

The Model 1 experiments were conducted with 52 flight legs and 82 ground arcs connecting 6 cities and 4 aircraft types. The flight schedules, including flight legs and ground arcs, were created by combining the actual flight timetables of Easyjet, an airline with similar characteristics to the Type 1 airline described in this study. The four aircraft types were created by using the properties of Airbus A319 and A321neo, which are the actual operating aircraft of Easyjet. A319, a small aircraft with low fuel efficiency, was called No. 1. Based on this, an aircraft with the same fuel efficiency as No. 1 but with an increased number of passenger seats was created as No. 3. In a similar way, the A321neo, a large aircraft with high fuel efficiency, was called No. 4. The aircraft with the same fuel efficiency as No. 4 but with fewer passenger seats was created as No. 2. Since each flight leg has a different demand, a total of four aircraft types were created with only two different passenger capacities for the same fuel efficiency, to limit the disproportionate impact of the flight leg' s demand on aircraft allocation. The values of the main parameters are as follows. SAF, a carbon-reduced eco-friendly fuel, and TAF, a conventional fossil fuel, are priced at 1.03 euros/L and 0.47 euros/L, respectively. The penalty for violating the SAF mandate is 0.94euro/L, and the penalty for emitting excessive carbon greater than the number of carbon credits held is 0.1euros/kg. The initial value of the free allocation quota proportion alpha for carbon credits is 70 percent of the total carbon emissions emitted by airlines, and the market price for carbon credits is 0.08 euros/kg. The demand for each flight leg is created uniformly by the number of passenger seats in small and large-size aircraft. The flight legs and the ground arcs to be assigned in this experiment are shown in Figure 4.1.

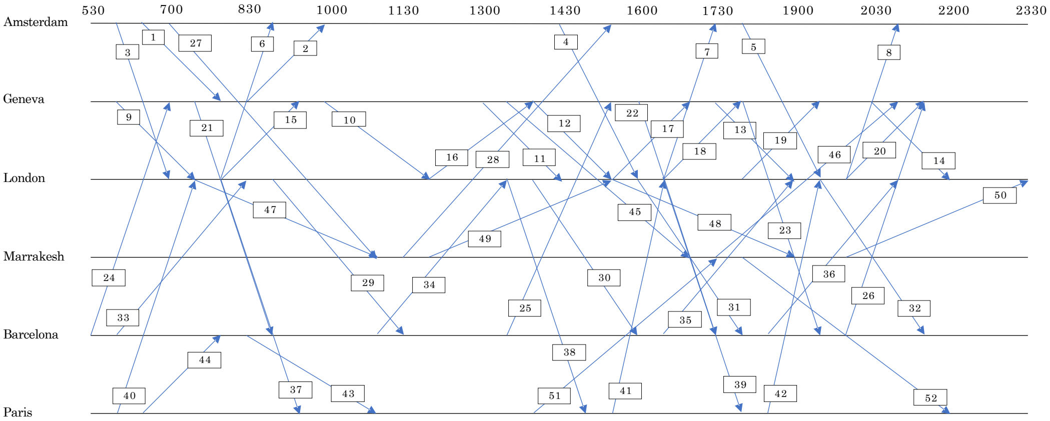


Figure 4.1: Flight schedule of Type 1 airline in Model 1 experiments

The aircraft type was assigned to the schedule of Figure 4.1 by the Basic Fleet Assignment Model (BFM), one of the existing methods of solving the fleet assignment problem, to find out the influence of Model 1 on the airline' s profit when the SAF policy is introduced. If the solution derived by the BFM is substituted for the problem situation of Model 1 described in Chapter 3, a lousy profit of -4,238 euros is derived. On the other hand, by Model 1 of this study, which considers the SAF mandate and carbon transactions, an airline profit of 11,365 euros was obtained. The results of this experiment are shown in Figure 4.2. Referring to Figure 4.2, the BFM and Model 1 have the same profit value when carbon policies do not exist. However, if the SAF mandate is applied only at the origin of the flight leg, the airline can gain an additional 15,604 euros from using Model 1. Furthermore, if the SAF mandate assumed tight regulations to apply at both origin and destination, the additional profit of the airline through Model 1 increases to 22,929 euros. In other words, it is estimated that as SAF regulations become tight, the profits that airlines can gain through Model 1 will increase. The EU' s SAF mandate has been strengthened so far and is expected to continue a similar tendency in the future, so the benefits this model can bring to airlines are expected to grow.

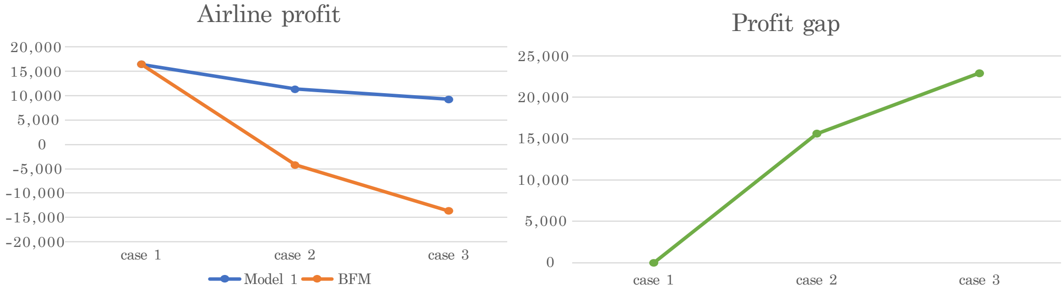


Figure 4.2: Airline's total profit and profit gap based on the two models

However, in the case of carbon emissions in the same situation, it can be seen that the reduction amount in carbon emissions of the BFM is greater than the reduction amount of Model 1. This is because Model 1 only aims to maximize the airline' s total profit. An ETS is operating to prevent companies from using various strategies to decrease the effect of environmental regulations, that is, to incentivize companies to operate eco-friendly airlines. However, Figures 4.2 and 4.3 show that companies still have to minimize carbon emissions reduction.

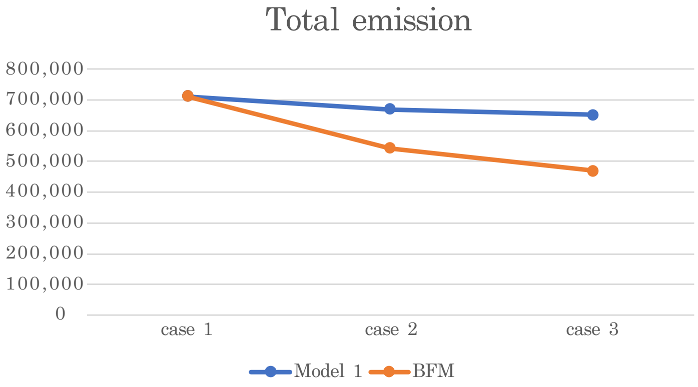


Figure 4.3: Airline's total emission amount based on the two models

In order to investigate the effect of Model 1 in more detail, we look at the factors that make up the BFM and the profit of Model 1. The airline' s ticket sales revenue is more significant in the BFM model, which does not take into account additional factors such as SAF or ETS. In addition, as shown in Figure 4.3, the carbon emissions penalty in the BFM is also lower because the carbon emissions by the BFM are lower than in Model 1. However, by Model 1 presented in this study, navigation cost, or fuel cost, is overwhelmingly reduced. Considering that both models have an SAF violation penalty of zero and both meet the SAF mandate, it can be confirmed that what type of aircraft is assigned on which flight legs, that is, the fleet assignment, has a significant impact on the airline' s profit level. Furthermore, the best strategy airlines can take in the current situation of various carbon policies is to meet the SAF mandate with a minimum amount of SAF without considering carbon emissions penalties or ETS. However, these strategies can vary, depending on how carbon prices are set in the market.

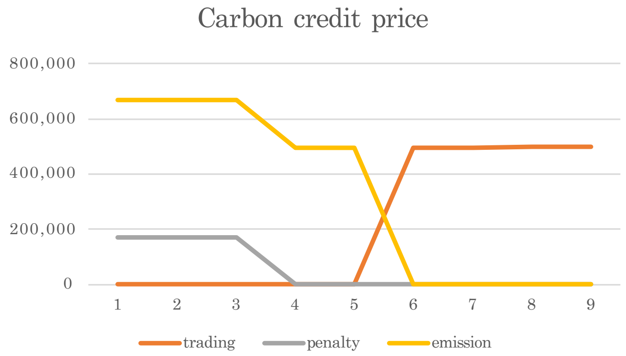


Figure 4.4: Airline's carbon transaction strategies depend on the market price of carbon credit

Despite the various efforts to increase SAF utilization, the optimal strategy that airlines can take is to use minimal SAF, even if they have to pay carbon emissions penalties. In addition, even if the parameters were changed and the experiment was carried out assuming a wide variety of cases, it was scarce for airlines to use the SAF more than the mandate and make a decision to sell residual carbon credits to the market due to the reduction of carbon emissions. This is presumed to be because of the excessively low market price of carbon credits. Recently, the market price of carbon credits has been 0.08 euros/kg, and the experiments in this study show that airlines have the incentive to reduce carbon emissions actively and sell residual emissions when carbon prices are above 0.22 euros/kg, that is, the market for carbon credits can be activated. Figure 4.4 shows the airline' s optimal strategy according to the market price fluctuation of carbon credits. If the carbon price is below 0.21 euros/kg, it is most advantageous for airlines to make the choice of emitting maximum carbon, even if they pay the maximum carbon emissions penalty, but do not violate the SAF mandate. If carbon prices increase between 0.21 and 0.22 euros/kg, the best strategy the airline will take is to emit carbon exactly as much as the free allowance quota of carbon credits allocated by the government, pay no carbon penalty, or sell residual credits. Finally, if the market price of carbon exceeds 0.22 euros/kg, airlines must use the SAF more than the mandate to emit carbon below the allocated credits, and the remaining credits must be sold to the market. In other words, it can be interpreted that the carbon credit market will be activated only when the carbon price exceeds 0.22 euros/kg. Furthermore, violating the SAF mandate is never advantageous for airlines in all three cases of carbon credit prices. This is because the SAF penalty per unit charged for SAF violation is currently set very high, at 0.94 euros/kg. Figure 4.5 shows that if the SAF penalty is reduced to less than 0.3 euros/kg, it can be confirmed that an environment will be created for airlines to violate the SAF mandate to gain additional profits.

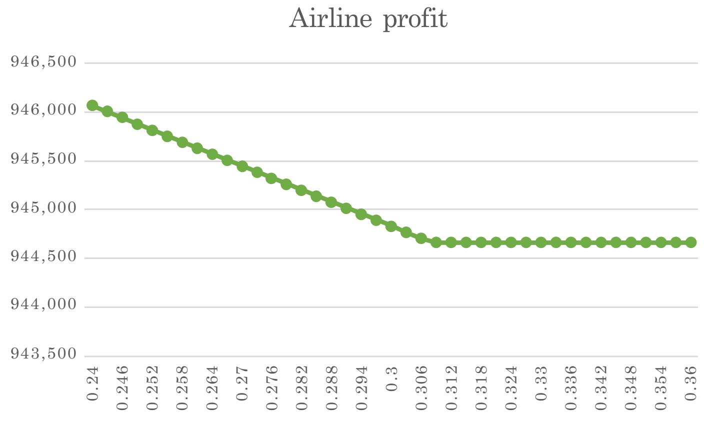
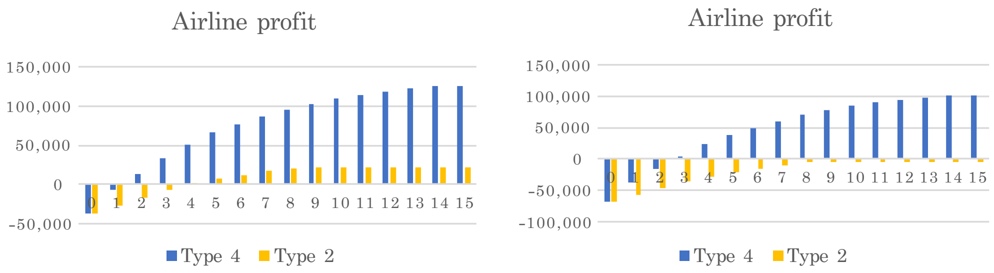


Figure 4.5: Airline's total profit depend on the SAF penalty cost per unit

This study referred to the flight schedule and the aircraft type held by Easyjet, a European airline, to design the experiment of Model 1. At last count, Easyjet has ninety-six A319 models, the No. 1 aircraft type referred to in this study, but has only fifteen A321neo models, the No. 4 aircraft type we refer to. The A319 is an out-of-date model, so Easyjet is gradually introducing a new model while retiring a large number of A319 models. This study examines the relationship between the number of aircraft owned by airlines and the corresponding airline' s profit in the context of introducing carbon policies. In order to analyze the benefits of introducing up-to-date high-efficiency aircraft to airlines, it was assumed that the airline had out-of-date low-efficiency aircraft only at first. In other words, this setup implies a condition in which an airline has sufficient aircraft to cover all routes but no efficient No. 2 and No. 4 aircraft. In this situation, if the airline introduces No. 2 aircraft, which are high-efficiency small-size aircraft, and No. 4 aircraft, which are high-efficiency large-size aircraft, one by one, the results described in Figure 4.6 are derived. The graph on the left side of Figure 4.6 shows the condition without carbon policies. It can be seen that the airline' s profit, which had a negative value when there was no high-efficiency aircraft, changed to a positive value when introducing aircraft No. 2 and aircraft No. 4 types. On the other hand, in the graph on the right side of Figure 4.6, which shows the condition with carbon policies, the introduction of aircraft No. 2 types, which are high-efficiency small aircraft, cannot make a positive profit for the airline and converge to the negative profit no matter how many aircraft are introduced. This means that airlines, which had purchased the latest high-efficiency aircraft simply to increase profit before carbon regulations, could be trapped in a structural condition in which they could not make positive profits without introducing high-efficiency, especially large-size aircraft, since carbon policies were introduced. While introducing up-to-date, expensive aircraft is clearly a huge investment for airlines, if they want to make enough profit even after carbon policies are introduced, they should consider introducing high-efficiency large-size aircraft.



(a) Without carbon policies (b) With carbon policies

Figure 4.6: Airline’s total profit based on the number of aircraft

In Model 1, a sensitivity analysis was performed on four parameters: the SAF price, the TAF price, the market price of carbon credits, and the proportion of total free allowance α, which affect the airline’ s total profit. In the sensitivity analysis, the values from -20 percent to +20 percent of each parameter were performed at a width of 1 percent, and all other values except for the changed parameter were kept the same. The analysis results are shown in Figure 4.7. In Figure 4.7, it was confirmed that p_t, which means the TAF price, had the most significant effect on the airline’ s profits. It is thought that this is the result of the fact that fuel costs account for about one-third of aircraft operating costs in general, and most of them are still accounted for by the TAF, not the SAF. The other sensitive parameter is α, which means the ratio of the free allowance quota of carbon that airlines can emit. α directly affects the amount of SAF and TAF that airlines must use, and the sensitivity of p_t, which is a TAF price, is very high, so the sensitivity of also seems to be high.

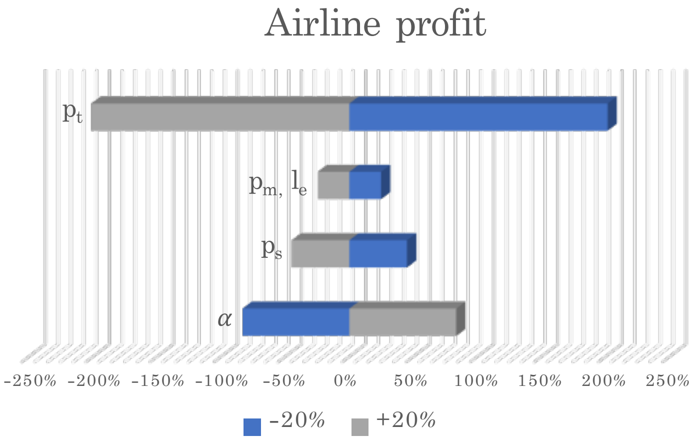


Figure 4.7: Sensitivity analysis of Model 1

4.2 Experiments for Model 2

Model 2 experiments were conducted with one country where the airline' s headquarters were located and ten other countries. The ten countries consist of four countries inside Europe and six outside Europe. One of the major South Korean airlines was referenced for the route of experiments. Unlike Type 1 airlines, which operate short-haul flight legs several times a day between neighboring countries, Type 2 flight legs operate particular routes once a day at most, so the time relationships between the legs were not considered. It is assumed that one type of aircraft operated on one route of a country repeatedly. The four aircraft types and parameters used in the experiment are identical to those used in the Model 1 experiment.

In the presence of carbon policies, including SAF, this study checked whether introducing code-share in this model can help decision-making in a way that increases airline profits. In the context of this experiment' s problem, the airline' s total profit is 53,5671 euros if the aircraft is allocated through BFM, which does not use code-share. In the same condition, using Model 2 enables code-share agreement results to abolish direct flight legs connecting countries 1, 2, 5, and 7 and change them to stopover flight legs passing through countries 3 and 8. In that case, the airline' s profit is 69,7966 euros. In other words, airlines can earn an additional profit of 16,2295 euros within this problem situation through Model 2 presented in this study. At this time, the profits of both the BFM and Model 2 tend to decrease, and the profit gap between models increases as the SAF quota becomes tighter than before. In other words, as in the Model 1 experiment, in the case of Model 2, it can be seen that the more carbon policies are strengthened, the more profits airlines can get from the model. As carbon policies are strengthened, overall airline profits decrease, and code-share can reduce the impact of policies.

Figure 4.8 shows the airline' s carbon emissions amounts of BFM and Model 2. Unlike Model 1, which had higher carbon emissions amounts and less carbon emissions reduction than BFM, in the experiments of Model 2, the emissions amount is clearly low, roughly half the emissions of BFM. However, it is difficult to interpret this, owing to airlines' carbon reduction efforts. Emissions were cut because several direct flights have been abolished, not that SAF usage has increased more than the quota. In other words, the fact that the amount of carbon emitted by the Type 2 airline has decreased does not mean decreased carbon emissions from the entire aviation industry. Model 2 experiments have confirmed that several long-haul direct flight legs tend to be divided into one direct flight leg to the hub country and short-haul legs connecting the hub with its surrounding countries by code-share. This can be interpreted as the airlines like Type 2 making code-share agreements with airlines like Type 1 that operate short-haul flight legs between neighboring countries. Considering that the reduction amount of emissions decreased in Model 1 experiments in the previous Chapter, it can be assumed that the reduced carbon in Model 2 transferred to Model 1. This is quite reasonable because although this study does not cover the interaction between Type 1 and Type 2 airlines, if Type 2 airlines' direct flights are changed via code-share agreements with Type 1 airlines, the number of flight legs operated by Type 1 airlines will increase.

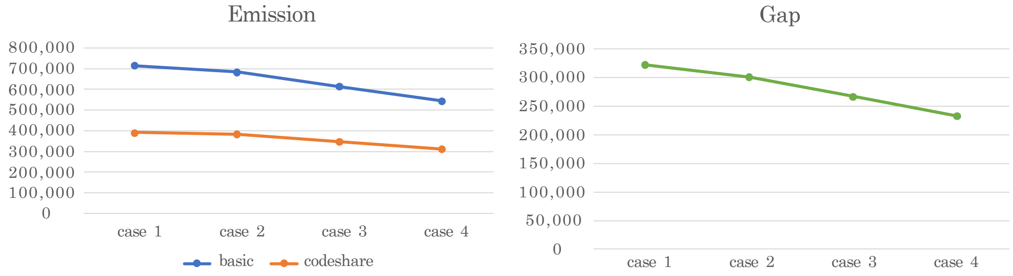


Figure 4.8: Airline's total emission amount and emission gap based on the two models

A detailed analysis of the difference between BFM and Model 2 is as follows. If Model 2 is used, the number of flight legs operated by Type 2 airlines decreases, and a large number of demands of the abolished legs are lost. Hence, the total amount of revenue of the airline decreases. However, the decrease in navigation costs caused by less SAF usage is about twice as large as the reduced revenue, which offsets this. In other words, for Model 1, the use of SAF was reduced through fleet assignment considering high SAF mandate areas, while for Model 2, the number of flight legs involving a high SAF mandate was reduced by code-share. In addition, reduced carbon emissions will lower the cost of the carbon penalty of Model 2. The additional benefits can also be obtained from revenue shared from code-share tickets. The code-share agreement benefits airlines even if it has zero percent of the revenue sharing proportion, because airlines like Type 2 can reduce the impact of the EU' s carbon policy by code-share with airlines like Type 1 that are already optimized for operating under EU' s carbon policies. This phenomenon can be interpreted as a hub-and-spoke method, which is one method of aircraft operation. The hub-and-spoke method, which was used a lot in the past, allocated large-size fuel-efficient aircraft to the journey of long-haul flights to hub airports and allocated relatively small-size aircraft to the short-haul flights connecting the hub airport and surrounding areas. However, nowadays, as the introduction of medium and small-size aircraft capable of long-haul flights due to the overall fuel efficiency of aircraft rises, there is a tendency that the number of direct long-haul flights that do not pass through the hub airport is increasing. However, through the Model 2 experiment, it can be considered that building a hub-and-spoke network, regardless of the available flight distance of the aircraft, can be beneficial for airlines. This is true because of the increase of environmental policies that can raise navigation costs proportionally to the flight distance.

To find out how the introduction of the SAF mandate affects airlines in this problem situation, Model 2 was solved for each of the cases in which the SAF mandate and the ETS do not exist, and for each of the cases in which both do exist. Without carbon policies, code-share results in unprofitable direct flight legs connecting countries 1, 5, and 7, and they should be eliminated and changed into stopover legs through country 3. In fact, flight legs operated by airlines are not always profitable, depending on the demand for each flight or the distance and environment of the route. Under the same condition, introducing carbon policies implies that the flight legs to be abolished should be 1, 2, 5, and 7. It implies that introducing carbon policies may lead to a decrease in the profitability of flight legs.

Unlike the airline in Model 1, which entrains a variety of alternative transportation options if flight legs are abolished, because the model usually operates short-haul flights nearby, Type 2 airlines may lose the direct way to go from one country to another if the route is eliminated. In fact, the aviation industry still abolishes existing routes owing to changes in profitability or circumstance and operates routes differently from season to season. Accordingly, the government or other related institutions provide subsidies in various ways to create aviation service for routes that are less profitable but must be operated due to high utility or having no alternative transportation available. The problem is that, as shown in the results of previous experiments, carbon policies may worsen the profitability of airlines and eliminate the existing routes. There are three commonly used methods of subsidy: reducing airport taxes paid by airlines by subsidizing airports where the unprofitable routes depart or arrive, directly subsidizing airlines, and subsidizing passengers who use the routes so that the airline can raise fares. In this study, these can be seen as fixed costs, total airline profit, and ticket fares in the model. From the airline' s point of view, if subsidies are received through airport tax reduction, the fixed cost of operating flight leg 2 will be reduced. In this experiment, which resulted in the abolition of direct routes 1, 2, 5, and 7, for route 2 to be operational again, the fixed cost of leg 2 must be lowered by 1,990 euros. In this case, airlines must require a subsidy of at least 1,990 euros. If airlines receive subsidies directly from the government, they must ask the government for at least the necessary cost to operate route 2. If route 2 is required to operate effectively, the airline' s profit was

69,5978 euros, 1,988 euros less than 69,7966 euros, the airline profit without route restrictions. In other words, airlines must require subsidies of at least 1,988 euros from related institutions to operate route 2. Finally, passengers using the route receive subsidies, which means an increase in fare price from the airline' s point of view. When calculating the appropriate amount by Model 2, it can be confirmed that route 2 is operated when the airline raises the fare price of route 2 by 13.3 euros. The number of passengers boarding route 2 is 150, so the total subsidy required is 1,995 euros. This shows that the most effective way to subsidize airlines to maintain routes that can be abolished due to the introduction of carbon policies in this experimental situation is to subsidize airlines directly. Given this, airlines can calculate a minimal amount of subsidies required with Model 2 depending on their specific operational situation.

In Model 2, a sensitivity analysis was conducted in the same manner as in the Model 1 experiment. The analysis results are shown in Figure 4.9. The results generally describe a similar tendency to Type 1 airlines, but it was confirmed that the sensitivity of p_s, which means the price of SAF, decreased by about half. That is because unlike Model 1, which aims to comply with the SAF mandate while incurring as little damage to profit as possible through aircraft allocation to all predetermined flight legs by fleet assignment, Model 2 is likely to abolish routes with a high SAF mandate and distribute demand via code-share. A sensitivity analysis was also performed on the two other parameters, β and γ, which exist only in the Type 2 experiment. The sensitivity of β, which indicates the proportion of the demand transferred from abolished direct routes to other stopover routes, was overwhelmingly high. Given this, the airlines need to use the model flexibly by changing the parameters to fit their own situations. On the other hand, γ, which means the revenue-sharing proportion of a code-share agreement, showed almost the slightest sensitivity among parameters. In other words, in the airline' s code-share process, the revenue-sharing proportion to be determined when signing a contract does not significantly affect airline profits. However, passengers' probability of choosing a layover route impacts airline profits significantly. Therefore, rather than focusing on the contract proportion in the agreement process, airlines should focus on minimizing passenger demand loss through route changes caused by code-share, such as layover times, passengers' preferences, and whether competitors have direct flights.

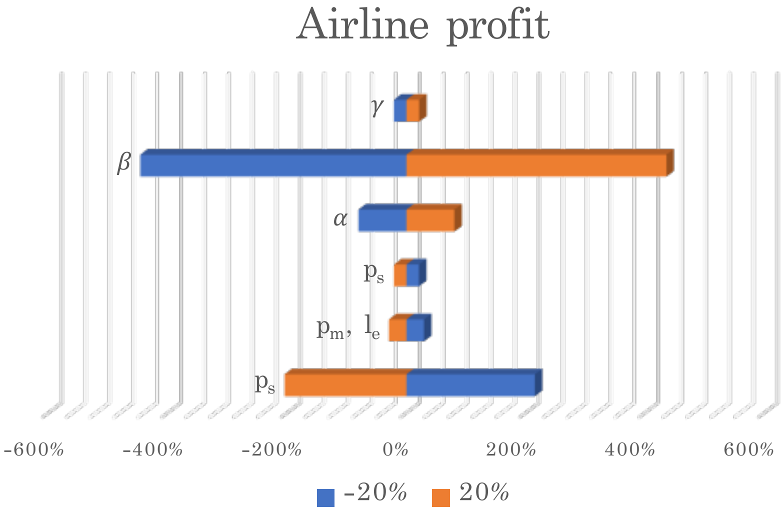


Figure 4.9: Sensitivity analysis of Model 2

Chapter 5

Conclusions

This study explores airlines' aircraft operation strategies following the introduction of the European Union' s SAF policy. In this study, airlines were divided into two types: inside Europe and outside Europe. The mathematical models are formulated according to the characteristics of airlines. In addition, in this study, numerical experiments are performed to propose various managerial insights into the two types of airlines. In the case of Type 1 airlines, Model 1 can reduce the decrease in profit due to the introduction of carbon policies. In addition, although it varies as the market price of carbon credits changes, it can be strategically advantageous to comply with the SAF mandate with only a minimum of SAF without considering the ETS or carbon penalty. Airlines do not benefit from breaking the SAF mandate if the current SAF penalty costs are maintained. Furthermore, after carbon policies are implemented, the number of high-efficiency large-size aircraft owned by airlines will significantly impact airline profit more than before. As carbon regulations become tight, airlines should be very active in investing in replacing existing low-efficiency aircraft with high-efficiency aircraft, especially high-efficiency large-size aircraft.

This paper suggests that in the case of airlines like Type 2, code-share can be used to reduce the impact of environmental policies on airline profit. This is because navigation costs of airlines can be significantly reduced, and they can also be helped by changing direct flights that have been less profitable due to carbon policies to stopover flights through neighboring countries by code-share. Although the supply of direct long-haul flights is increasing compared to the past hub-and-spoke operations due to the recent increase in aircraft fuel efficiency, this study claims that reducing carbon taxes and SAF usage by distance with hub airports could benefit airlines as carbon policies are introduced. Furthermore, not all flights are always positively profitable, but introducing carbon policies has made more routes less profitable. In the case of Type 2 airlines, there is often no alternative transportation, so related institutions need to subsidize such airlines to maintain unprofitable routes. This study showed that when airlines are trying to reduce the impact of carbon regulation by a code-share agreement, Model 2 can be used to calculate the amount of subsidies that must be paid through three frequently used subsidy methods.

There are several limitations to this study. First, this study does not consider changes in aircraft fuel efficiency due to surrounding environments such as the number of passengers or climate. In addition, in the code-share agreement, this study does not consider the lack of capacity of the partner airline. Also, it does not provide the airline’ s best solution in the face of change in passenger demand caused by code-share. Furthermore, this study does not consider the existence of interactions between the two types of aircraft. In other words, the model does not reflect the case where type 2 airlines and type 1 airlines make a code-share agreement to operate the hub-and-spoke system. Since the consideration can increase the practicality of this study’ s actual use in the real-world decision-making process, we propose further research that considers the interaction between the two types of airlines presented in this study in the context of introducing carbon policies.

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국문초록

기후 협약으로 새로운 환경 관련 규제들이 도입됨에 따라 전세계적으로 항공 산업에서의 탄소 배출량 감축에 대한 관심이 증가하고 있다. 이에 본 연구에서는 유럽연합의 탄소 배출 정책 하에서 항공사의 항공기 할당 및 코드셰어를 이용한 경로 재설정 문제를 다루었다. 특히 지속가능한 항공 연료 (SAF)의 이용과 관련 규제의 도입, 그리고 배출권 거래 시스템 (ETS)이 항공기 운영 정책에 미치는 영향을 탐색하였다. 항공사들을 특성에 따라 두 종류로 분류하여 분석을 수행하였으며, 각각의 경우에 대한 혼합 정수 선형 계획 모형을 제시하였다. 이 모형은 탄소 정책이 강화되는 환경 속에서 항공사들에게 추가적 이익을 발생시키며, 다양한 경영적 통찰력을 제공한다.

주요어: 지속가능한 항공 연료, 배출권 거래 제도, 탄소 배출권, 항공기 할당, 경로 재설정, 코드셰어

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