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Strategic airline operation considering the carbon constrained air transport industry

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ABSTRACT

The EU emissions trading system (EU-ETS) is the EU's policy to combat climate change by reducing greenhouse gas emissions cost-effectively. CO_2 emissions from aviation have been included in the EU-ETS since 2012, and all airlines operating in Europe are required to report and submit allowances against those emissions. The EU-ETS is only applied to flights that begin or end in EU territory, therefore one of the options non-EU based airlines use to deal with the EU-ETS requirements is aircraft reassignment or flight route adjustment. We investigate strategic airline operations that address the carbon constraints on the air transport industry. A mathematical model and algorithm are developed to derive efficient strategies for airline operations in terms of aircraft reassignment and route adjustment. The proposed mathematical model and heuristic algorithm are verified with a numerical example. The results of this study provide practitioners with insights when dealing with environmental restrictions on airlines.

1. Introduction

Many efforts are being made to prevent environmental pollution and achieve sustainable development in every field of industry and commerce. However, these various efforts tend to be most effective when they involve not only organizations inside a certain country, but also global actors and cooperation among many countries. Among such international efforts, the European Union Emission Trading Scheme (EU-ETS) is one of the most successful. The EU-ETS has applied international regulations on the emission of greenhouse gases (GHGs) such as CO_2 and CH_4. This scheme has been legislated by the EU council and parliament on the basis of the Kyoto Protocol agreements made during the Third Conference of the Parties at Kyoto, Japan, in December 1997. According to the Kyoto Protocol plan, developed countries that belong to Annex I (such as the EU and Japan) were to reduce their emissions of GHGs to 94.8% of their 1990 levels by 2012. Developing countries that belong to the Non-Annex nations (such as Korea and China) were to prepare and execute similar GHG reduction plans starting in 2012. To follow up the Kyoto Protocol's recommendations, the EU and three other countries (Iceland, Liechtenstein, and Norway) announced the EU-ETS, which was to be implemented in three phases. This scheme is a kind of “cap and trade” system, in which each country has a pre-assigned annual volume of GHG emissions, and the participants can buy or sell their own emissions rights to other countries in a trading market. The EU-ETS was implemented in a test drive phase I period (2005–2007), and since then it has steadily supplemented and strengthened its regulations in terms of the industries affected and goals set during its phase II (2008–2012) and phase III (2013–2020) periods.

Since 2012, the EU-ETS has applied GHG limitations to the air transport industry. Although carbon emissions from air transport are currently below 4% of the EU's total annual emissions, this industry's proportion of total GHG emissions is expected to increase to 15% of all such emissions by 2050. The initial EU-ETS regulations have been a subject of controversy around the world, because the EU has decided to apply its emission restrictions to all airlines that operate in EU territory, regardless of their nationality. According to Airlines for America, the overall additional cost of applying EU-ETS restrictions to U.S.-based airlines will amount to USD3.1 billion between 2012 and 2020. In addition, the China Air

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Transport Association has estimated that the required additional cost to Chinese airlines will be RMB0.8 billion over the same period. However, at the request of the International Civil Aviation Organization (ICAO), the application of the EU-ETS to the aviation industry was delayed until after 2020. The ICAO began developing a global market-based mechanism in 2013, announced its application policy to the aviation industry in 2016, and agreed to apply it from 2020. That is, the EU-ETS was introduced to EU airlines from 2012 but was deferred to non-EU airlines until 2020. As a result, the aviation industry is also partially subject to the EU-ETS sometime, and many airlines have tried to develop countermeasures to reduce or avert the adverse effects of this regulation scheme.

According to an interview with the staff of a Korea-based airline, possible countermeasures that airlines may take against EU-ETS restrictions include the following:

- assigning new highly fuel-efficient aircraft to the EU routes
- adding fuel-efficient devices to existing aircraft
- adjusting the airline's flight network
- resetting the aircraft's center of gravity
- reducing the weight of aircraft loading materials
- finding more efficient air routes
- using biomass jet fuel, which is exempt from carbon credits

Of these possible approaches, we consider only the countermeasures that involve aircraft reassignments and flight route adjustments. Because the EU-ETS is applied only to flights that either originate or terminate in EU territory, airlines that are not based in the EU can, to some degree, cope with the EU-ETS by means of aircraft re-assignment and flight route adjustment. When the more fuel-efficient aircraft are assigned to EU routes, the amounts of carbon emission for EU flights can be reduced. In addition, when certain flight routes that are affected by the EU-ETS are adjusted as shorter hauls, the amounts of carbon emission counted under the EU-ETS quotas can be reduced.

2. Previous studies

Various studies have dealt with the fleet assignment problems involved in determining the types of aircraft for each flight leg within given planning periods and under various restrictions, such as maintenance schedules or crew assignments. Barnhart et al. (2002) assigned various types of aircraft to specific flight legs in a case study using data from a major airline to evaluate a proposed model. Sherali et al. (2006) dealt with the fleet assignment problem by considering schedule design, aircraft maintenance routing, and crew scheduling. Rushmeier and Kontogiorgis (1997) studied a large-scale fleet assignment problem as a mixed-integer multicommodity model. Barnhart et al. (2009) introduced a sub-network fleet assignment model and imposed composite decision variables to represent simultaneous assignments. Sherali and Zhu (2008) developed a two-stage fleet assignment model that considered demand uncertainty. The authors made higher-level family assignment decisions in this model's first stage and assigned the appropriate types of aircraft in the second stage, based on the results of the first stage. In addition, Sherali and Zhu compared their stochastic model with a traditional deterministic model to verify their model's efficacy.

Some researchers have investigated flight network design, which involves both flight scheduling and aircraft routing. Aircraft routing involves deciding which aircraft type to operate between each origin-destination pair and how many times to operate per unit of time (day or week). Barnhart and Cohn (2004) examined the expensive and highly constrained resources of the airline industry. They also explored approaches for optimizing airline schedules to improve decision making and increase airline profits. Sarac et al. (2006) addressed the aircraft maintenance routing problem as subject to maintenance resource availability. These authors used a branch-and-bound algorithm to obtain optimal solutions. Chou et al. (2008) proposed an inequality-based multiple-objective genetic algorithm to solve the aircraft routing problem. Rexing et al. (2000) and Lohatepanont and Barnhart (2004) developed integrated models to simultaneously consider both the flight schedule design problem and the fleet assignment problem. Some researchers have developed methods for designing flight schedules and applied them to the actual airline industry. Abara (1989) dealt with the fleet assignment problem as an integer linear programming issue and proposed a model that is used by American Airlines. Erdmann et al. (2001) handled the flight network design for charter airlines and developed a combined branch-and-bound algorithm.

Several additional studies have dealt with the aircraft routing problem and the fleet assignment problem simultaneously (Barnhart et al., 1998; Haouari et al., 2009, 2011). The fleet assignment problem involves determining which type of specific aircraft will operate on each flight leg between all origin-destination pairs. Liang and Chaovalitwongse (2013) proposed a network-based model to solve the weekly aircraft maintenance routing problem along with the weekly fleet assignment problem. The aircraft maintenance routing problem requires aircraft routing to consider maintenance operations as well as the transportation of passengers. Sherali et al. (2013) dealt with the flight scheduling, fleet assignment, and aircraft-routing processes while considering various additional factors such as demand recapture or itinerary-based demands.

In recent years, airlines have continued their efforts to reduce environmental pollution, and several researchers have explored environmental issues in the air transport industry. Both Sgouridis et al. (2011) and Sheu and Li (2013) conducted studies on airline policies and strategies for a carbon-constrained air transport industry. Sgouridis et al. (2011) considered five policies to reduce carbon emissions: 1) improvements in technological efficiency, 2) improvements in operational efficiency, 3) use of alternative fuels, 4) shifts in demand, and 5) carbon pricing. Sheu and Li (2013) investigated the effects of carbon permits under cap-and-trade schemes. Some other studies have dealt with the environmental fees or penalties that are imposed on airlines. Lu (2009) compared the effects of environmental fees under two business models: full service carriers (e.g., British Airlines, Air France, and KLM) and low cost airlines (e.g., EasyJet). Carlsson (2002) derived optimal flight environmental fees for two types of airline markets: monopolies and duopolies.

3. Model development

3.1. Problem description

In this study, we deal with strategic options for airline operations in terms of aircraft reassignment and flight route adjustment. Our concern is to minimize the total operational costs caused by a carbon-constrained market situation such as that under the EU-ETS. Note that we focus on airlines that are not based in the EU. Fig. 1 shows an example of a certain airline that is based in Korea and serves cities around the world with various types of aircraft. Each circle indicates an origin or destination city, and each curved line represents a flight route.

Among these flight routes, those that begin or end in EU territory come under EU-ETS emission restrictions. Therefore, when the more fuel-efficient aircraft are reassigned from non-EU flight routes to EU routes, an airline can reduce its total carbon emissions on its EU flight routes. Note that the amount of carbon emission is

Fig. 1. Flight routes between ICN and other cities operated by airline based in Korea.

proportional to fuel consumption. In addition, suppose that a long-haul EU flight route is adjusted to pass through certain layovers, so that only the flight route from the layover city to the EU city of destination is subject to EU-ETS limitations. In that case, the number of customers traveling from their city of origin to their EU destination may decline, due to the additional flight time imposed by the layover. At the same time, the altered route may attract certain new customers who wish to travel from the layover city to the EU destination city on the newly opened flight route. Various additional costs can be incurred due to a layover. Additional operational costs and fuel costs can be imposed because of the increased number of landings, take-offs, and taxiing. Ground costs and maintenance costs should also be considered. Aircraft rearrangements and flight route adjustments can lead to customer dissatisfaction, customer demand variation, and additional costs. We discuss these detailed cost issues in the final section.

Therefore, airline managers should carefully consider any such changes. Another option for airlines is to buy carbon emission permits on the official carbon trading market, which can allow them to exceed their preassigned emission quotas without incurring penalties.

3.2. Notations

i, j:	Indices for possible served city nodes.
m:	Index for flight leg.
n:	Index for aircraft.
V:	Set of all possible served city nodes.
V_c:	Set of city nodes that are influenced by the carbon constraint.
V_{nc}:	Set of city nodes that are not influenced by the carbon constraint.
p_{ijmn}:	Revenue when aircraft n is operated on the mth flight leg from node i to j.
vc_{ijmn}:	Variable cost when aircraft n is operated on the mth flight leg from node i to j.
x_{ijmn}:	Binary decision variable for a flight leg. An aircraft n that operates on the mth flight leg from node i to j receives a value of 1, and otherwise 0.
fc_n:	Fixed cost of aircraft n.
y_{jn}:	Binary variable for flight assignment. An aircraft n that is permitted to operate at node j receives a value of 1, and otherwise 0.
$c_{penalty}$:	Penalty cost per for each ton of CO_2 emissions exceeding the target quantity.
q_{ijmn}:	Quantity of CO_2 emitted when aircraft n is operated on the mth flight leg from node i to j.
c_{trade}:	Trading cost per ton to purchase additional permits for CO_2 emission.
q_{trade}:	Amount of additional permits for CO_2 emission purchased.
$q_{maxtrade}$:	Maximum quantity of emissions that can be purchased through the carbon trading market.
q_{free}:	The assigned quantity of penalty-free CO_2 emissions allowed to an airline.
T_n:	Maximum available time for aircraft n.
t_{ijn}:	Flight time when aircraft n is operated from node i to j.
s_{jn}:	Preparation time for aircraft n at node j.
y_n^{max}:	Maximum number of city nodes served by aircraft n.
S:	Arbitrary subset of city nodes. $S \cup \bar{S} = V$.
z_S^n:	Binary variable that takes a value of 1 if aircraft n has a flight leg that passes between the city nodes of an arbitrary subset S, and otherwise 0.
w_S^n:	Binary variable that takes a value of 1 if aircraft n has a flight leg that passes both in and out of arbitrary subset S, and otherwise 0.

3.3. Assumptions

The following assumptions are considered in the proposed modeling process:

1. In a given planning period, each flight route is served a maximum of M times.
2. Each aircraft should be assigned to both legs of a round-trip flight. In other words, if an aircraft n is assigned to the mth flight leg from node i to j, then it should also be assigned to the mth flight leg from node j to i.
3. When the mth flight leg from node i to j is operated by aircraft n, the revenue, the variable cost, and the quantity of CO_2 emissions are predetermined.
4. If certain flight legs have a city node that is influenced by the carbon-constraint regulation, then the sums of CO_2 emissions from those flight legs are restricted by the regulation. The quantity of CO_2 that the airline can emit without cost is determined annually by the regulating authorities.
5. The airline can purchase additional CO_2 emission allowances by paying the trading cost per ton of CO_2. However, there is an upper limitation on the quantity of CO_2 emissions that the airline can purchase.
6. If an airline violates the carbon-constraint regulation, a penalty cost is imposed on the airline, according to the amount of emissions in excess of its limit.
7. The airline has N number of aircraft and all aircraft have the same capacity.
8. The flight time, the CO_2 emissions from node i to j, and the preparation time to departure at node j can be set differently according each aircraft.
9. In the EU-ETS, an airline can sell its remaining CO2 emission allowance to other airlines. However, we consider airlines that need to implement countermeasures against the EU-ETS because of the shortage of CO2 emission allowances. Therefore, the option to sell CO2 emission allowances is not considered in this study.
10. The various additional costs associated with layover are reflected in the variable cost that occurs when operating from node i to node j.

11. The hub-and-spoke network is not considered, as no hub city nodes are modeled in this study.

3.4. Mathematical model

Based on the assumptions and notations described above, the overall mathematical model formulation is developed as follows.

Maximize

$$\sum_{i\in V}\sum_{j\in V}\sum_{m\in M}\sum_{n\in N}\left(p_{ijmn}-vc_{ijmn}\right)\cdot x_{ijmn} - \sum_{n\in N} fc_n\cdot \mathrm{Min}\left\{1,\sum_{i\in I} y_{in}\right\} - c_{penalty}\cdot \mathrm{Max}\left\{\begin{array}{c}\left(\begin{array}{c}\sum_{i\in V}\sum_{j\in V}\sum_{m\in M}\sum_{n\in N} q_{ijmn}x_{ijmn}\\ -\sum_{i\in V_{nc}}\sum_{j\in V_{nc}}\sum_{m\in M}\sum_{n\in N} q_{ijmn}x_{ijmn}\end{array}\right)\\ -q_{trade}-q_{free},0\end{array}\right\} - c_{trade}\cdot q_{trade} \quad (1)$$

subject to

$$T_n-\sum_{i\in V}\sum_{j\in V}\sum_{m\in M}\left(t_{ijn}+s_{jn}\right)\cdot x_{ijmn}\geq 0,\quad n\in N \quad (2)$$

$$x_{ijmn}=x_{jimn},\quad i,j\in V,\ m\in M,\ n\in N \quad (3)$$

$$x_{iimn}=0,\quad i\in V,\ m\in M,\ n\in N \quad (4)$$

$$\sum_{n\in N} x_{ijmn}\leq 1,\quad i,j\in V,\ m\in M \quad (5)$$

$$\sum_{n\in N} x_{ijmn}-\sum_{n\in N} x_{ij(m+1)n}\geq 0,\quad i,j\in V,\ m=1,\cdots,M-1 \quad (6)$$

$$y_{in}\cdot y_{jn}\geq x_{ijmn},\quad i,j\in V,\ m\in M,\ n\in N \quad (7)$$

$$\sum_{j} y_{jn}\leq y_n^{max},\quad n\in N \quad (8)$$

$$z_S^n\geq x_{ijmn},\quad i,j\in S,S\subset V,S\notin\phi,V,\ m\in M,n\in N \quad (9)$$

$$z_S^n+z_{\overline{S}}^n-1\leq w_S^n,\quad S\subset V,S\notin\phi,V,\ n\in N \quad (10)$$

$$w_S^n\leq z_S^n,\quad S\subset V,S\notin\phi,V,\ n\in N \quad (11)$$

$$w_S^n\leq z_{\overline{S}}^n,\quad S\subset V,S\notin\phi,V,\ n\in N \quad (12)$$

$$w_S^n\leq\sum_{i\in S}\sum_{j\in\overline{S}}\sum_{m\in M} x_{ijmn},\quad S\subset V,S\notin\phi,V,\ n\in N \quad (13)$$

$$0\leq q_{trade}\leq q_{maxtrade} \quad (14)$$

$$x_{ijmn},y_{in}\in\{0,1\},\quad \forall i,j,m,n \quad (15)$$

3.4.1. Objective function

The objective function is defined as in equation (1). This function stands for the total profit of the airline in an air transport market that has carbon-constraint regulations. The objective function is the sum of all revenue minus the sum of all related costs (including variable costs of operations, fixed costs of aircraft, penalty costs for exceeding carbon emission limits, and trading costs).

3.4.2. Constraints

Constraint (2) indicates that each aircraft should be assigned and operated within a given planning period. Constraint (3) ensures that each aircraft is assigned to both legs of a round-trip flight. According to constraint (4), the departure and arrival nodes for each flight leg cannot be same. That is, there is no flight leg with the same departure and arrival node. Constraint (5) indicates that the maximum number of aircraft assigned to the *m*th flight leg from node *i* to node *j* is 1. Constraint (6) means that the aircraft assigned to the *m*th flight leg between a certain pair of cities can be assigned only to the $(m+1)^{\text{th}}$ flight leg for that city pair. According to constraint (7), an aircraft that has a permit to operate at node *i* and *j* can operate the flight leg from node *i* to node *j*. Constraint (8) sets the maximum number of operating nodes served by aircraft *n*. Constraints (9) to (12) are developed to represent the definitions of binary variables. Constraint (9) describes the binary variable z_S^n, and constraints (10) to (12) describe the binary variable w_S^n. With these variables, we can prevent the generation of sub-tours through constraint (13). If there is a sub-tour for a series of flight legs operated by aircraft *n*, then that aircraft cannot cover those flight legs alone. Constraint (14) indicates that the amount of additional permits for purchasing CO_2 emissions on the carbon trading market has an upper limit. Please note that $q_{maxtrade}$ is a parameter indicating the upper limit of CO2. If there is no limit, the numerical value of this parameter can be set high. Note that with this parameter, we can perform sensitivity analyses, such as how the model and solution behave with various limits.

Constraint (15) represents a set of decision variables, which are 0–1 binary variables.

4. Solution procedure

The genetic algorithm is a well-known metaheuristic algorithm used to generate optimal or near-optimal solutions of the developed mathematical model as formulated by Holland (1975). This algorithm is applied in situations in which it is difficult to find an optimal solution with general mathematical techniques. In studies related to the air transport industry, the genetic algorithm is generally used to solve complex mathematical model formulations. Soolaki et al. (2012) proposed an integer linear programming approach and adopted a genetic algorithm to solve airline boarding problems, such as how to reduce passenger boarding times. In addition, Liu et al. (2011) introduced concepts and techniques from complex network theory and applied an effective, efficient genetic algorithm to optimize airline route networks. Moreover, Levine (1996) and Chen et al. (2013) dealt with airline crew scheduling problems in various situations by using a genetic algorithm. The overall procedure of the general genetic algorithm is depicted in Fig. 2.

For this study, the flight route network should be designed as between *I* number of cities, and the quantity of carbon trading on the official trading market should be determined within available limitations with the proposed mathematical model formulation. To generate optimal or near-optimal solutions, we suggest an efficient genetic algorithm as a solution method and design a chromosome as shown in Fig. 3. Initially, we consider the *I* by *I* matrix plus one slot to represent the flight route design and the quantity of carbon trading, respectively. Then, the number of genes is I^2+1. However, because we assume a flight route design with a round trip concept,

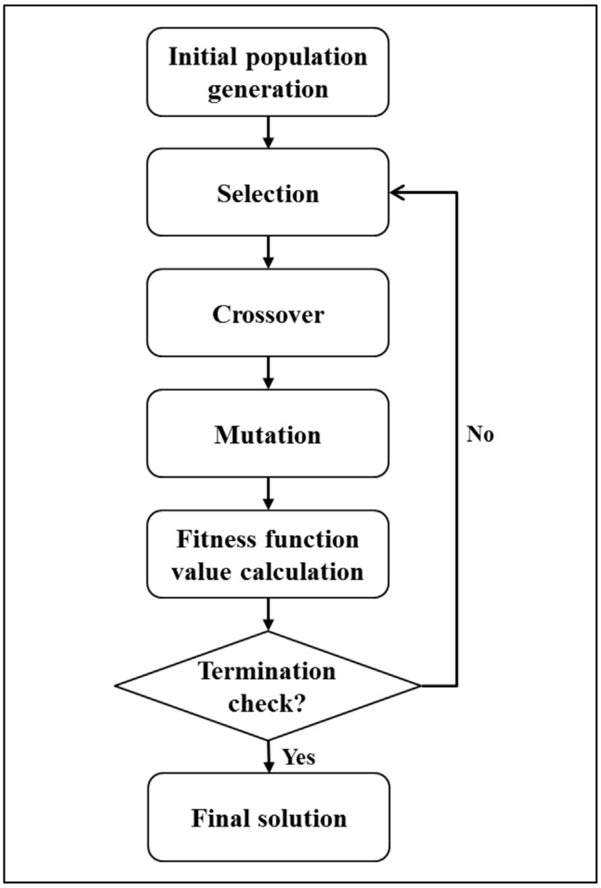

Fig. 2. Overall procedure of genetic algorithm.

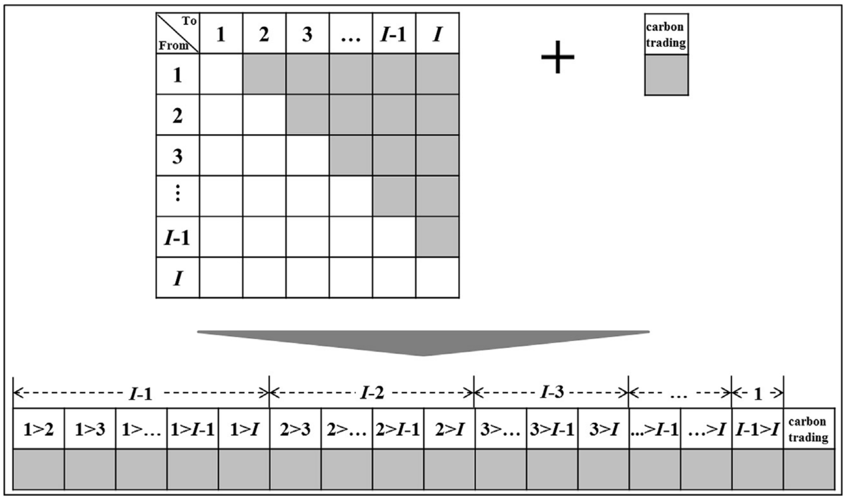

Fig. 3. Configuration of chromosome.

we only need information representing the gray-colored gene. Therefore, we suggest a configuration of the chromosome as shown in Fig. 3, and the number of genes is $I(I-1)/2+1$. A laconic configuration of the chromosome is very important, because it can significantly affect the performance of the genetic algorithm.

In the initial step for generating a solution, an integer between 0 and M (i.e., the maximum number of flights) is randomly assigned at the first $I(I-1)$ gene to present the flight route design. A real number between 0 and $q_{maxtrade}$ is also randomly given at the last gene to describe the carbon trading quantity.

In the selection step, we choose N chromosomes from the population via the roulette wheel rule. The possibility of selecting a certain chromosome varies with the quality of the fitness function value of that chromosome. However, the initial population does not execute this step, due to the lack of information about the fitness function value.

In the crossover step, two points on two particular chromosomes are randomly selected and exchanged to generate two new chromosomes. In the mutation step, one point of a certain chromosome is randomly chosen and assigned a new feasible value, which also creates a new chromosome. Those two steps are done to maintain the variety of the population.

In the fitness function value calculation step, each chromosome of the population is evaluated on the basis of a mathematical model formulation. If a chromosome breaks certain constraints, it receives a predetermined penalty whose value varies with the degree of importance given to those constraints.

Two kinds of criteria are generally used in the termination check step. The chromosomes that belong to the population are changed until their ratio of the same features reaches 95%; the overall procedure is then stopped. In addition, when the iteration concerning the creation of a new generation process is repeated a predetermined number of times, the overall procedure can be terminated.

5. Numerical examples

5.1. System parameters

To verify the proposed mathematical model formulation and the developed genetic algorithm, we examine a hypothetical example. In this example, we assume a hypothetical airline based in Korea that is expected to serve nodes that are subject to EU-ETS regulations. In addition, nine cities can be potentially served by this airline. City 1 is in Korea, cities 2 through 7 are in the EU, and cities 8 and 9 are outside the EU. Each flight route from city i to city j is regarded as operating no more than three times during the planning horizon, which is set as 1 week. The flight route distance and the flight time between city i and city j are described in Tables 1 and

Table 1
Flight route distance [km] between city *i* and *j*.

	1	2	3	4	5	6	7	8	9
1	–	9096	9971	8753	8626	9073	8781	6812	6592
2	9096	–	1263	359	639	341	777	2102	2507
3	9971	1263	–	1482	1448	1054	1249	3191	3447
4	8753	359	1482	–	362	417	613	1770	2153
5	8626	639	1448	362	–	481	306	1745	2026
6	9073	341	1054	417	481	–	492	2165	2494
7	8781	777	1249	613	306	492	–	1984	2200
8	6812	2102	3191	1770	1745	2165	1984	–	634
9	6592	2507	3447	2153	2026	2494	2200	634	–

Table 2
Flight time [hours] between city *i* and *j*.

	1	2	3	4	5	6	7	8	9
1	–	12	13	12	11	12	11	10	9
2	11	–	2	1	2	1	2	3	4
3	12	2	–	2	3	2	2	5	5
4	11	1	2	–	1	1	2	3	3
5	10	2	3	1	–	1	1	3	3
6	11	1	2	1	1	–	1	3	3
7	10	2	2	2	1	1	–	3	3
8	9	3	5	3	3	3	3	–	2
9	8	4	5	3	3	3	3	2	–

2. The preparation times before long-haul flights and short-haul flights are assumed to be 4 h and 2 h, respectively. Moreover, the revenue for standard operation per flight between city *i* and city *j* is presented in Table 3. The variable cost for a standard operation is regarded as half its revenue. This cost is designed to be proportionally reduced according to the number of operations for the same flight route, either by 0%, 10%, and 30% or by 0%, 5%, and 15%. This cost design is set to prevent the concentration of flights on the most profitable flight routes. Initially, the number of passengers per flight is assumed as 125. In addition, the total carbon emitted during a flight between city i and city j is calculated using a carbon emission coefficient of 0.152859 kg per kilometer per passenger, according to the flight distance and the number of passengers per flight. This is one of the limitations of this study. In fact, because a lot of fuel is consumed at takeoff and landing, fuel consumption is not proportional to distance; however, as accurate consumption is unknown, this example assumes that fuel consumption is proportional to distance. The penalty cost and the trading cost per ton of emissions are regarded as \$300 and \$50, respectively. An assigned penalty-free carbon emission quota is set as 88% of its initial emissions level, and the permitted trading quantity is no more than 10% of that. Moreover, one of the aircraft is less efficient, and two are more efficient, and all aircraft can serve no more than five cities with the same capacity. The variable cost and the carbon emission for these two types of aircraft are weighted as 1.05 and 1.10 and 0.95 and 0.90, respectively.

Table 3
Revenue [USD] for single standard operation between city *i* and *j*.

	1	2	3	4	5	6	7	8	9
1	–	250	270	175	230	240	220	220	220
2	250	–	40	25	30	30	35	90	65
3	270	40	–	35	40	25	35	80	80
4	175	25	35	–	25	25	35	55	70
5	230	30	40	25	–	30	30	55	60
6	240	30	25	25	30	–	35	65	70
7	220	35	35	35	30	35	-	75	60
8	220	90	80	55	55	65	75	–	25
9	220	65	80	70	60	70	60	25	–

5.2. Experimental method

Using the system parameter values and the problem situations explained in the previous section, we test two kinds of cases—one for before the EU-ETS and one for after the EU-ETS. These tests are done to confirm the effects of the EU-ETS in terms of the profits and amounts of carbon emission involved. Although the proposed mathematical model formulation is developed for the case after the EU-ETS, we can very easily find an optimal or near-optimal solution for the case before the EU-ETS. To eliminate the effects of the EU-ETS, we simply set the value of the penalty cost as 0. We can then obtain the optimal solution for the flight route design and aircraft reassignment without consideration of the EU-ETS. By comparing the cases before and after the EU-ETS, we can measure its effects in terms of profits and carbon emissions.

5.3. Results comparison

To confirm the effects of the EU-ETS, the experimental results of both cases are compared at the level of each aircraft. The three aircraft are labeled as aircraft A, B, and C; aircraft B and C are the more efficient aircraft, and aircraft A is the less efficient aircraft. The variable cost and the carbon emission quantity are set as 105% and 110% of standard operation for aircraft A and 95% and 90% for aircraft B and C.

The generated flight routes for aircraft A, B, and C in both carbon constraint scenarios are depicted in Fig. 4. The experimental results in terms of the revenue, variable cost, carbon emission quantity (both the totals and the amounts subject to EU-ETS), trading quantity, penalty, profit, and flight routes are presented in Table 4. In the case of the inefficient aircraft (aircraft A), the airline decreases its long-haul flight routes between city 1 and city 7, but adds short-haul flight routes between cities 2, 4, and 6. As a result, revenue is reduced by (348, 750−304, 400)/348, 750 = 12.72%, and the variable cost is diminished by (188, 475−168, 131)/188, 475 = 10.79%. In addition, the quantity of carbon emission from the inefficient aircraft is reduced by 4124.3−3171.6 = 952.7 tons, and the total quantity of carbon emission decreases by as much as 8831.0−8160.3 = 670.7 tons. In the case of the efficient aircraft (aircraft B and C), the airline tends to concentrate more on the most profitable routes rather than operating a diversity of flight routes, and it reduces the operation of short-haul flight routes. The numbers of served flight routes is adjusted from 15 to 13. Therefore, the revenue is reduced by {(313,750 + 270,400) − (283,375 + 262,750)}/(283,375 + 262,750) = 6.96%, and the variable cost is also diminished by {(159,808 + 142,381) − (144,103 + 135,108)}/(144,103 + 135,108) = 8.23%. In addition, the quantity of carbon emission from the efficient aircraft increases by (3169.6 + 2901.0) − (3001.8 + 2786.8) = 282.0 tons. In terms of the carbon constraint, the quantity of carbon emissions in the case before the EU-ETS is 8831.0 tons, which was reduced to 8160.3 tons in the case after the EU-ETS. Therefore, the quantity of free preassigned carbon emissions is 8831.0 × 0.88 = 7771.3 tons. As a result, the excess quantity of carbon emitted in the after-EU-ETS case is 8160.3−7771.3 = 389.0 tons, which is covered by trading on the official carbon trading market.

To cope with the EU-ETS limitations, the airline attempts to reduce its carbon emissions while keeping its profit margin. For its countermeasures, some long-haul flight routes for the inefficient aircraft are reduced, and the number of flight routes served by the efficient aircraft is decreased to avoid inefficient routes. Following those variations, the unsatisfied customer demand for flights between EU cities tends to be met by increasing the short-haul flight

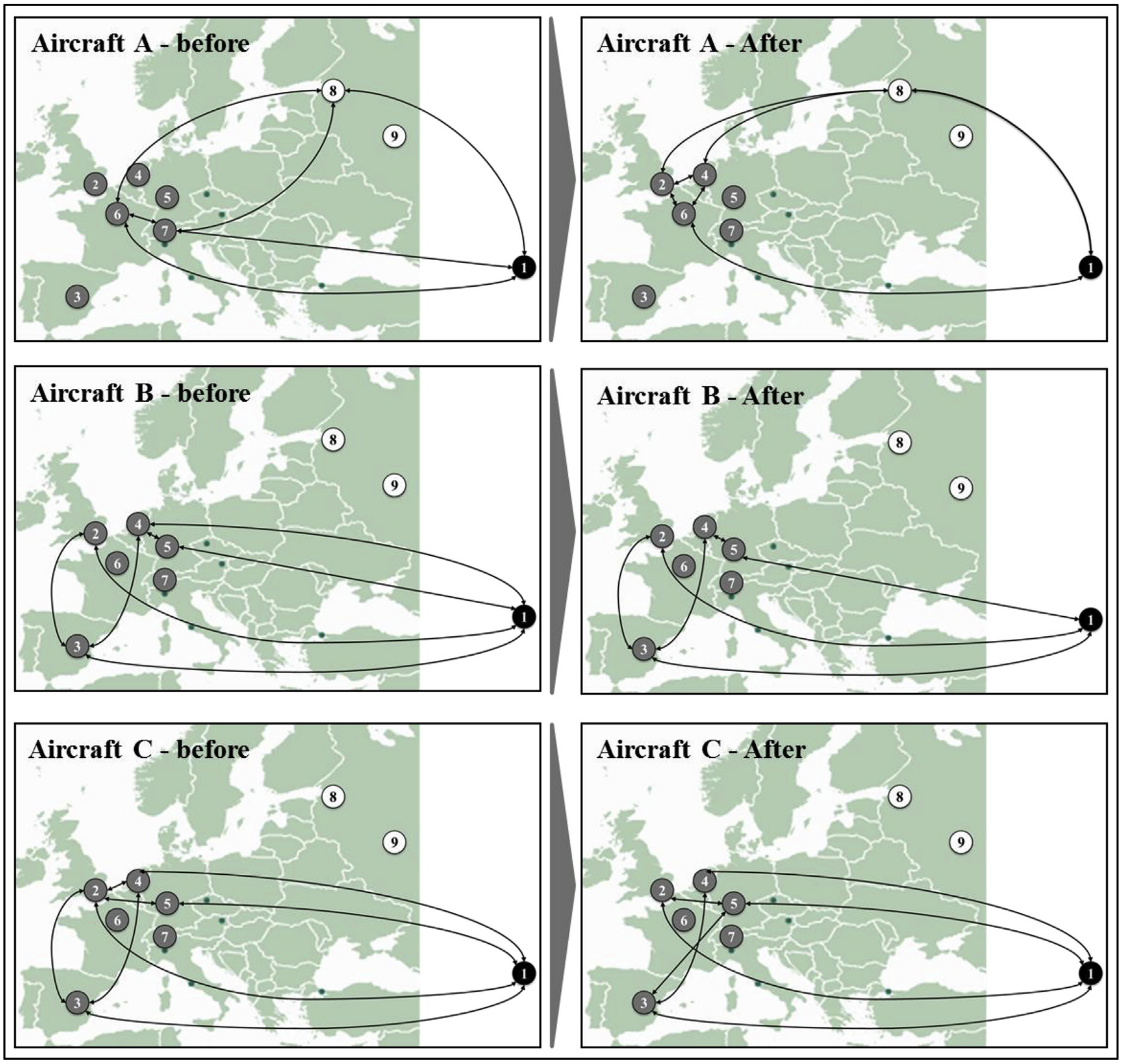

Fig. 4. Generated flight routes for aircraft A, B, and C before and after EU-ETS carbon constraint.

Table 4
Experimental results before and after EU-ETS carbon constraints.

	Before			After		
	A	B	C	A	B	C
Revenue [USD]	348,750 894,875	283,375	262,750	304,400 888,550	313,750	270,400
Variable cost [USD]	188,475 467,686	144,103	135,108	168,131 470,320	159,808	142,381
Carbon emission quantity [tons] (Total)	4124.3 9912.9	3001.8	2786.8	3171.6 9242.2	3169.6	2901.0
Carbon emission quantity [tons] (subject to EU-ETS)	3042.4 8831.0	3001.8	2786.8	2089.7 8160.3	3169.6	2901.0
Trading quantity [tons]	–			427.4		
Penalty [USD]	–			–		
Profit [USD]	**427,189**			**396,860**		
Generated flight routes	1–6:2 1–7:2 1–8:2 6–7:1 7–8:1	1–2:2 1–3:1 1–4:1 1–5:1 2–3:1 3–4:1 4–5:1	1–2:1 1–3:1 1–4:1 1–5:1 2–3:2 2–4:3 2–5:1 3–4:2	1–6:2 1–8:2 2–4:3 2–6:2 2–8:2 4–6:1 4–8:1	1–2:2 1–3:2 1–5:1 2–3:2 3–4:1 4–5:1	1–2:1 1–3:1 1–4:1 1–5:2 2–5:2 3–4:1 3–5:1

routes by the inefficient aircraft. Meanwhile, the demand for medium-haul flight routes can be satisfied by the more efficient aircraft. Through such efforts involving aircraft re-assignment and flight route adjustment, the airline can reduce the quantity of carbon emissions by 670.7 tons (= 7.6%) for the EU-ETS–related flight routes. In addition, the airline buys additional emissions permits to deal with its remaining excess emissions totaling about 389.0 tons. Moreover, the profit of this airline decreases by almost 7.1% due to application of the EU-ETS standards.

6. Conclusions

This study explores strategic airline operations in response to a carbon-constrained air transport market. Moreover, the study aims to confirm the effects of carbon-constraint–related regulations such as those of the EU-ETS for a theoretical airline based outside the EU. We develop a nonlinear mathematical model formulation and propose an efficient genetic algorithm to consider countermeasures involving aircraft reassignment and flight route adjustment. With this numerical example, we verify our model and our solution method using hypothetical system parameters as applied to the EU-ETS situation. According to the resulting comparison between the cases before and after the EU-ETS, we find that an airline tends to decrease the long-haul flight routes assigned to inefficient aircraft and increase the short-haul flight routes. The more efficient aircraft tend to be concentrated on several longer flight routes rather than serving a greater diversity of routes. Through these changes to operations, the quantity of carbon emission from inefficient aircraft is reduced and that from efficient aircraft is increased. As a result, under the EU-ETS restrictions, the overall quantity of carbon emissions for the hypothetical airline decreases, but its profit is also reduced. In addition, some carbon emission permits must still be purchased to avoid penalties for exceeding the EU-ETS carbon emission limits. However, if the price of the carbon emission allowance is too low, airlines will respond to the EU-ETS by simply purchasing a carbon emission allowance without altering their business operations.

Of course, the proposed optimization model with an analytical approach has certain limitations. Due to the nature of the analytical model, some approximations and assumptions are necessary. The cost structure implicitly includes a high level of approximations: for example, adding a segment means adding additional take-off, taxiing, and landing; maintenance costs are required due to cycles (number of landings and takeoffs); maintenance is needed just due to operating aircraft in and around an airport; additional personnel are needed for operations, crews and maintenance; and there are the cost of gate acquisition, gate fees, landing fees, safety, and so forth. Moreover, there is a complex cost structure for fuel consumption. For instance, for the same type of aircraft, the fuel consumed by flying one leg of 2000 nm is usually much less than the fuel consumed by flying two legs of 1000 nm each. Therefore, for a practical issue, airline managers should consider these detailed cost issues in the fixed and variable cost framework proposed in the model. As the detailed cost structure depends on the airline's policy, regulations, and operational rules, we cannot include all of them in a general modeling framework. However, once readers understand the concept and cost structure of the proposed model, they will be able to incorporate their own issues into it. We will propose how to incorporate these technical details into the cost structure in a follow-up study.

Furthermore, we must also emphasize that the current model assumes that the fuel consumption rate is homogeneous for a given aircraft regardless of the distance it flies and the number of landings and take-offs included. This assumption is required for the linear nature of the proposed optimization model. If the rate is time-invariant and variable as a function of landings and takes-offs, a nonlinear model is required. Considering this nonlinearity would be a valuable future research topic.

Again, this study can provide airline managers with insights on methods to reduce the costs of carbon-constraint–related regulations in terms of aircraft rearrangements and flight route adjustments. In addition, our study may help government policymakers to evaluate the design of carbon-constraint–related regulations for the air transport industry or similar industries.

In future research, we intend to introduce time windows to each flight route to help generate a more complete flight network design that includes maximal aircraft routing. We also intend to consider other metaheuristic methods to find more exact solutions for more complex and realistic situations. Moreover, more realistic data should be adopted that reflect the actual fuel consumption and so forth.

Last, we understand that the biomass jet fuel exemption and the varying costs of fuel based on feedstock are also critical issues for the reduction of greenhouse gases in the airline industry. Although we do not explicitly discuss and incorporate the issues in our proposed mathematical model, they could be included with some modifications. We propose this topic for a future study.

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