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Research Article

Air Traffic Efficiency Analysis of Airliner Scheduled Flights Using Collaborative Actions for Renovation of Air Traffic Systems Open Data

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The increase in air traffic worldwide requires improvement of flight operational efficiency. This study aims to reveal the potential benefits, namely, savings on fuel consumption and flight time, which are expected for Japanese airspace, by statistically evaluating the operational efficiency defined by average differences of fuel consumption, flight time, and flight distance between the original and the optimized flight of domestic flights in Japan. The aircraft position and time data used in this study were obtained from Collaborative Actions for Renovation of Air Traffic Systems Open Data—the radar data released by the Japan Civil Aviation Bureau. Flight information, such as air data and fuel flow, is estimated by applying meteorological data and aircraft performance model to the position information of radar data. Each reconstructed trajectory is optimized in terms of flight fuel consumption and flight time with an assumed cost index (CI). Dynamic programming is used as the trajectory optimization method. The flight fuel consumption and flight time of the optimized flight are compared with the original values to evaluate the operational efficiency. Herein, approximately one-third of 1-day data, i.e., 1087 cases of four aircraft types, are analyzed with reasonable CI settings. Our research findings suggest that flight fuel consumption and flight distance can be saved by 312 kg and 19.7 km, respectively, on average for the object flights. Following a statistical comparison between the original and the optimized flights, it was observed that two types of features, namely, flying on a detoured path and flying with nonoptimal altitude and speed in the cruise phase, are major factors which deteriorate the total operational efficiency in terms of fuel consumption, flight time, and flight distance.

1. Introduction

With regard to the significant increase in air traffic worldwide, by 2027, Japanese air traffic is expected to increase by half of that recorded in 2005 [1]. The reasons for the rise in air traffic include the increasing number of tourists from Asian countries [1], vigorous participation of low-cost carriers, and frequent operation by small or single-aisle airplanes, which constitute the majority of the aircraft in the global market [2]. An increase in air traffic leads to various issues, e.g., increased fuel consumption, increased pollution caused by emissions, and flight safety deterioration. These are urgent issues that are common to all Air Navigation Service Providers, aircraft companies, operators, and tourists. The economic efficiency and convenience of air travel are affected by not only effects of having to extend flight distance to meet the required time of arrival to enter congested zones but also flight distance extension by airspace restrictions. This is particularly true in Japan, where flyable airspace is intricately restricted, mainly because of military reasons [3]. Increased traffic increases the workload of air traffic controllers, likely leading to an increased probability of incidents such as near-miss in a congested airspace. In 2010, the Japanese government has established Collaborative Actions for Renovation of Air Traffic Systems (CARATS) as a roadmap for developing the future air traffic system in Japan. Similarly, many research projects were implemented under the NextGEN program in the United States and SESAR in Europe. One of the important plans for the future Air Traffic Management (ATM) system is an innovative change from the existing airspace-based operation to trajectory-based operation (TBO), which considers the flight route from departure to arrival as one continuous trajectory in a unified airspace over the whole flight information region. The TBO is foreseen to become a key component to realize more efficient operation for achieving an ideal air traffic system because each aircraft can achieve its maximum performance if the most preferable flight state and route are selected. Consequently, economic efficiency could be drastically improved. TBO is also expected to lead to growth in air traffic capacity.

This research reveals the potential benefits which mean savings on fuel consumption and flight time expected in the case of Japanese airspace, by evaluating the quantified operational efficiency for the purpose of gaining knowledge that can be utilized for realizing TBO. Average differences of fuel consumption, flight time, and flight distance between the original and the optimized flight are calculated for the statistical evaluation of operational efficiency. The actual operational data gathered by a surveillance radar system was used in the analysis.

ATM has gained considerable interest among the research community in the last 20 years. References [4–6] present trail-blazing research on aircraft performance optimization. Reference [4] introduces various fixed end-point flight path optimization problems, such as fuel minimization with a fixed range, time minimization with a fixed range, and fuel minimization with fixed range and fixed time conditions. References [5, 6] demonstrate trajectory optimization in a vertical plane considering the direct operating cost for subsonic transport aircraft. In all these studies, indirect methods such as calculus of variations or singular perturbation theory were used. Reference [7] is one of the works most related to the present study. The research considers explicit time constraints in vertical flight planning and proposes a heuristic-based soft dynamic programming (DP) approach. The term "4D-trajectory optimization" is used in the research; however, the demonstrated results are limited to vertical flight planning.

Many studies explored operational performance and potential benefit evaluation [8–12]. In Japan, the ATM research group in Kyushu University evaluated the achievable potential benefits of the Japanese air traffic system. Some of their works in which actual operational data were used are described below.

(1) Reference [13] established flight parameter estimation method by using GPS (Global Positioning System) data recorded in an airborne airliner cabin and numerical weather data. Reference [14] evaluated the potential benefit by applying the flight parameter estimation and flight trajectory optimization to the recorded GPS data.

(2) The optimal flight trajectories were compared with original flight data stored in the quick access recorder (QAR). The QAR data were provided by a Japanese airline.

(3) References [15, 16] analyzed operational efficiency of the arrival flights inbound to Tokyo International Airport by using the secondary surveillance radar (SSR) data. This SSR was operated experimentally by the Electronic Navigation Research Institute in Japan.

(4) Reference [17] evaluated effectiveness of arrival management system of a European airport by using automatic dependent surveillance broadcast (ADS-B) data.

This research focuses on the potential benefit for more flight cases by using the methodologies developed in those works. Recently, surveillance radar data, CARATS Open Data [18], were used in ATM research in Japan. These data were accessible by the Japan Civil Aviation Bureau (JCAB) in February 2015 to promote R&D in the field of ATM. In this paper, the data are described as "CARATS Open Data" or simply "Open Data." These data contain larger error than GPS data because of the measurement performance of radars; however, these data are the most appropriate to evaluate overall operational efficiency in Japan because they contain surveillance information of all the aircraft flying throughout the Japanese airspace in keeping with the instrument flight rule (IFR). Miyazawa et al. used Open Data and revealed the benefits of introducing the arrival management system [19]; nevertheless, they focused on a congested airport where significant improvement is expected and did not consider flights between other airport combinations.

In this research, the operational efficiency of Japanese domestic flights, including those between comparatively noncongested airports, is analyzed. Operational efficiency is evaluated by average difference between the original flight and the optimal one in terms of the flight fuel consumption, flight time, and flight distance. Existing analysis methods, such as flight parameter estimation and four-dimensional flight trajectory optimization [14–17], are applied to the Open Data to calculate the original and optimal flight fuel consumption and flight time. In this research, four dimensions are the three positional dimensions and time; therefore, flight trajectory is optimized in terms of these four variables. Multiple flight cases consisting of climb, cruise, and descent phases are analyzed; thereafter, the features of unfavorable flights that might have affected the efficiency are identified from the obtained results. This research is expected to aid examination of the measures in R&D of CARATS by demonstrating the factors that may lead to bottlenecks in improving the operational efficiency by TBO.

2. En Route Surveillance Radar Data

2.1. Outline of CARATS Open Data. An overview of CARATS Open Data is presented in Table 1. The object data comprise 2012 annual data released in February 2012. It consists of 42-day data, which were recorded over a week of the odd months from May 2012 to March 2013. The data were recorded and assembled by the Air Route Surveillance Radar of the Air Navigation Services Department of JCAB.

2.2. Object Data. The major aircraft types from the domestic flights on July 15th (Sun), 2012, were extracted. On this day, a total of 3644 flights were made and 40 aircraft types were employed. The aircraft types are listed in the descending order of number of flights in Table 2.

This paper targets 1087 flights, a summation of the domestic flights from Type-A to Type-D, which are limited to

Table 1: Overview of CARATS Open Data [18, 20].

Record period	2012	May 7th (Mon)	to 13th (Sun)
		July 9th (Mon)	to 15th (Sun)
		September 3rd (Mon)	to 9th (Sun)
		November 5th (Mon)	to 11th (Sun)
	2013	January 7th (Mon)	to 13th (Sun)
		March 4th (Mon)	to 10th (Sun)
Objective	Airliner flying in IFR		
Flight	Approx. 3600 per day		
Items	Time, Virtual flight number, Latitude, Longitude, Pressure altitude, and Aircraft type		
Record cycle	Approx. 10 s		
Source	RDP (Radar Data Processing System) data and FDPS (Flight Data Processing Section) data in all four Area Control Centers (ACCs) in Japan		

Table 2: Number of flights (July 15th, 2012).

A/C type	Total	Domestic	Others
Type-A	630	466	164
Type-B	498	291	207
Type-C	310	155	155
Type-D	303	175	128
Type-E	205	0	205
Type-F	178	178	0

jet aircraft. Additionally, flight data corresponding to a height above 10000 [ft] are analyzed because clean configuration assumption is reasonable in this range.

3. Evaluation Method for Operational Efficiency

3.1. Aircraft Model. Operational efficiency evaluation in this work consists of two analyses: flight parameter estimation and flight trajectory optimization (Sections 3.2 and 3.3, respectively). This section describes the aircraft model used in both analyses.

Governing Equations. Three-degree-of-freedom equations were used in the analyses. The following conditions were assumed:

(i) Aircraft is a point mass.

(ii) Roundness of the Earth is neglected.

(iii) Quasi-steady flight is assumed. The change in the direction of the velocity vector is negligible because the flight path angle changes gradually in the motion of the passenger aircraft.

The governing equations determined by these assumptions are as follows [14]:

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{1}{(R_0 + H)\cos\phi}\left[V_{TAS}\cos\gamma_a \sin\psi_a + W_x(\phi,\theta)\right] \tag{1}$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = \frac{1}{R_0 + H}\left[V_{TAS}\cos\gamma_a \cos\psi_a + W_y(\phi,\theta)\right] \tag{2}$$

$$\frac{\mathrm{d}H}{\mathrm{d}t} = V_{TAS}\sin\gamma_a \tag{3}$$

$$m\frac{\mathrm{d}V_{TAS}}{\mathrm{d}t} = T - D - mg\sin\gamma_a - m\frac{dW}{dt}\cos\gamma_a \tag{4}$$

$$m\frac{\mathrm{d}\gamma_a}{\mathrm{d}t} = L - mg\cos\gamma_a + m\frac{dW}{dt}\sin\gamma_a = 0 \tag{5}$$

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -\mu. \tag{6}$$

Aerodynamic Model. Aerodynamic forces, lift, and drag are expressed in (7) and (9). The parabolic drag polar model in a clean configuration is used. The side force is not considered as the sideslip angle is negligible.

$$L = \frac{1}{2}\rho V_{TAS}^2 S C_L \tag{7}$$

$$D = \frac{1}{2}\rho V_{TAS}^2 S C_D \tag{8}$$

$$C_D = C_{D0} + K C_L^2. \tag{9}$$

3.2. Flight Parameter Estimation. Fuel consumption is an important quantity that defines air traffic efficiency. The model-based approach to estimate fuel consumption is introduced in this section. The author's research group developed a novel and effective method to calculate fuel consumption from the GPS position and time data recorded in an airborne airliner cabin [13]. They found that the fuel consumption can be estimated with high accuracy from the aircraft position and time data. The process of flight parameter estimation from original flight trajectories is introduced in Figure 1. This process is also explained in previous papers [16, 19]. Flight parameters such as true airspeed (TAS), calibrated airspeed (CAS), and Mach number are estimated from the position and time data by applying the temperature and wind velocity data stored in meteorological grid point value (GPV) data. These meteorological data were provided by the Japan Meteorological Agency [21]. Performance variables such as lift-to-drag ratio, thrust, and fuel flow were calculated by using the BADA (Base of Aircraft Data) model, which was developed and is maintained by EUROCONTROL [22]. The flight path climb angle relative to air γ_a is obtained from (3) using the estimated TAS. By substituting γ_a into (10), lift coefficient C_L can be obtained.

$$C_L = \frac{(mg\cos\gamma_a - m(dW/dt)\sin\gamma_a)}{(1/2)\rho V_{TAS}^2 S} \tag{10}$$

This C_L introduces drag D following (9) and (8); therefore, thrust T can be estimated from (4). Fuel flow μ is generally expressed as shown in (11) with thrust-specific fuel consumption c_{TSFC}.

$$\mu = c_{TSFC} T \tag{11}$$

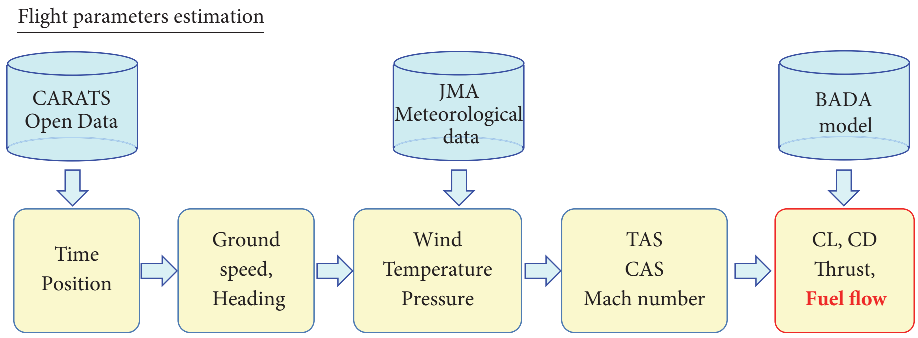

FIGURE 1: Flow of flight parameters estimation.

In the BADA model, c_{TSFC} is modeled as a function related to flight state. BADA revision 3.11 is used in this study. The quality of the meteorological GPV data and BADA performance model directly influences the accuracy of estimated flight parameters. By comparing the obtained parameters with onboard flight data, which was provided by an airline, in three studies [23–25], it was revealed that the model and data have sufficient quality to yield accurate flight parameters for use in air traffic efficiency analysis.

The process of flight parameter estimation is applied to object radar data. The estimated fuel flow includes errors caused by meteorological data, performance model, and aircraft mass difference. Aircraft mass information was not provided from the radar data; hence, the reduced value of the BADA reference mass is used as the initial mass value. 80% (for Type-A and Type-B) and 90% (for Type-C and Type-D) of BADA reference mass were assumed as the initial mass values in the analyses. These reduction rates are considered to be reasonable judging from the coincidence between the calculated optimal trajectory and the original one. Although these errors cannot be eliminated completely, the validity of the obtained results is still maintained. From a different point of view, this method is useful as fuel consumption, which should be known to quantify the operational efficiency, can be estimated for arbitrary flight trajectories.

3.3. Four-Dimensional Flight Trajectory Optimization

3.3.1. Objective Function. Fuel consumption and flight time can be calculated for arbitrary flight trajectories by the meteorological data and performance data, as mentioned in the previous section. Moreover, flight trajectories can be optimized for a given performance index by using the meteorological data and performance model in a manner identical to that used for parameter estimation, assuming identical initial and final positions and velocities. Three significant quantities, namely, flight fuel consumption, flight distance, and flight time, are calculated to evaluate air traffic efficiency. The original trajectories are optimized by considering a performance index that incorporates fuel consumption and flight time. This performance index J_k of the kth aircraft is defined as

$$J_k = \int_{t_{0,k}}^{t_{f,k}} \left[\mu_k(t) + \frac{m_k}{m_0} a_k \right] dt \tag{12}$$

where $\mu_k [kg/s]$ is fuel flow and $(m_k/m_0)a_k$ is a weighting parameter for the flight time. Further, m_k is the initial mass value of the kth aircraft, and m_0 is the representative mass, which is set to normalize the impact of time adjustment. In this analysis, m_0 is set as the mean value of the BADA reference mass of the target aircraft types. Although the second term in (12), i.e., time cost, can be evaluated equivalently with the fuel cost by introducing the weighting parameter a_k, coefficient (m_k/m_0) is required to avoid the changes in the influence of time adjustment depending on scale of the aircraft. This weighting parameter a_k is strongly related to the so-called cost index (CI) set into the flight management system. The performance index is the direct operating cost C [$] [5, 6] itself,

$$C_{k,dollars} = \int_{t_{0,k}}^{t_{f,k}} \left[C_{fuel} \cdot \mu_k(t) + C_{time} \right] dt \tag{13}$$

where C_{fuel} is the fuel cost [$/kg] and C_{time} is the time cost [$/s] in this equation. The CI is defined as time cost [$/h] per fuel cost [cents/lb] [26].

$$CI_k = \frac{C_{time}\,[\$/\mathrm{h}]}{C_{fuel}\,[\mathrm{cents/lb}]} \tag{14}$$

Now, the relationship between a_k and CI is introduced below. Both sides of (12) are first multiplied by the constant value C_{fuel} [$/kg].

$$C_{fuel} \cdot J_k = \int_{t_{0,k}}^{t_{f,k}} \left[C_{fuel} \cdot \mu_k(t) + C_{fuel} \cdot \frac{m_k}{m_0} a_k \right] dt \tag{15}$$

A Comparison of this equation with (13) yields the following relationship.

$$\frac{C_{time}\,[\$/\mathrm{s}]}{C_{fuel}\,[\$/\mathrm{kg}]} = \frac{m_k}{m_0} a_k \tag{16}$$

The relationship between a_k and CI is obtained as shown in (17) by multiplying (16) with the conversion factors.

$$CI_k = \frac{C_{time}\,[\$/\mathrm{h}]}{C_{fuel}\,[\mathrm{cents/lb}]} = \frac{3600 \cdot C_{time}\,[\$/\mathrm{s}]}{100 \cdot 0.4536 \cdot C_{fuel}\,[\$/\mathrm{kg}]} = 79.37 \frac{m_k}{m_0} a_k \tag{17}$$

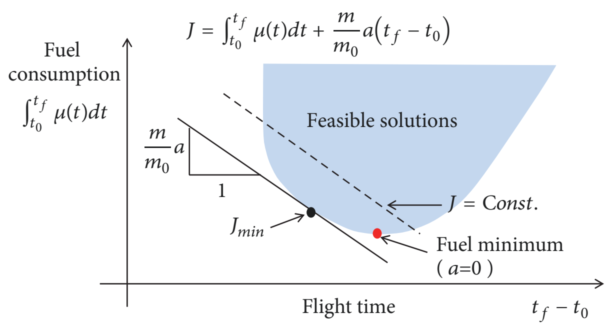

Figure 2: Relationship between feasible solutions and weighing parameter.

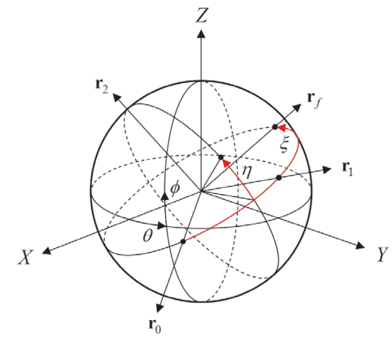

Figure 3: (ϕ, θ) polar coordinate system and (ξ, η) coordinate system.

Figure 2 explains the relationship between weighting parameter a and the performance index. The weighting parameter is equivalent to the slope of the tangent to the boundary of the feasible solutions, i.e., the optimal solutions for various weighting parameters form a Pareto front. Thus, CI is a free parameter for each performance index to be optimized; therefore, it is generally set according to the policies of airline operators.

3.3.2. Grid Settings for Dynamic Programming. Various flight trajectory optimization methods have been studied in the field of optimal control theory. The methods are roughly classified into two categories: indirect method and direct method [27]. In direct methods, a finite number of parameters indicate the trajectory and are solved as a parameter optimization problem. With the revolution in the processing capacity of computers, direct methods have been widely used in recent years. The representative methods used in the flight trajectory optimization are the direct collocation method [28, 29] and pseudospectral method [30]. This research uses DP as an easy-to-handle optimization method, considering the overall applicability and usability. In [31], DP is explained as follows.

> *"Bellman has generalized the Hamilton-Jacobi theory to include multistage systems and combinatorial problems and he calls this overall theory dynamic programming."*

He established the theory as a Hamilton-Jacobi-Bellman (HJB) equation. DP trajectory optimization involves solving the HJB equation as a combinatorial problem with quantized grid points. The optimal flight trajectory is obtained by selecting the grid points that are set in a state space such that the performance index denoted by (12) is minimized. Detailed four-dimensional trajectory optimization calculation by DP is introduced in the next subsection. The four dimensions are the three positional dimensions (ϕ, θ, H) and the time-related dimension V. Setting the state space using all these variables is computationally expensive because of a major drawback of DP, called the "curse of dimensionality." Hence, variables (ϕ, θ) in the polar coordinates are transformed into a great-circle angle and laterally deviated angle (ξ, η), as illustrated in Figure 3.

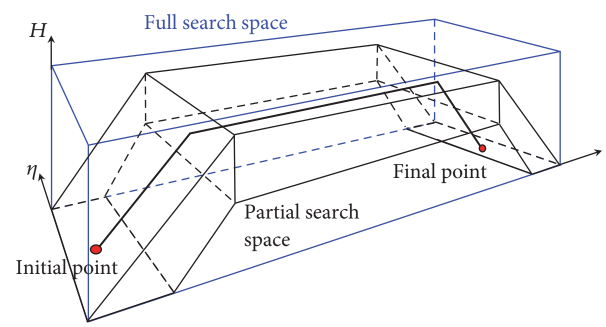

Figure 4: Search space for dynamic programming (V axis is not shown).

Furthermore, the independent variable, i.e., time, is substituted by the variable ξ. Consequently, the state space is defined by the three variables (η, V, H) and the independent variable ξ. The blue frame in Figure 4 shows the state space for the conventional method of DP trajectory optimization. For simplicity, V axis is not shown. To reduce computational time, optimization calculation is performed in the trapezoidal space, which moves as the solution is improved. This gradient-based approach was termed the Moving Search Space Dynamic Programming [32]. In this analysis, a simple equidistant grid is set in the search space.

3.3.3. Dynamic Programming Trajectory Optimization. DP optimal trajectory can be calculated by the following algorithm.

$$J_{opt_i}(\mathbf{x}_i, \xi_i) = \min_{\mathbf{u}} \left[\Delta J|_{\xi_i}^{\xi_{i+1}} + J_{opt_{i+1}}(\mathbf{x}_{i+1}, \xi_{i+1}) \right] \qquad (18)$$

Here, the first term on the right-hand side denotes the fraction of the objective function between ith and $i+1$th stages of independent variable ξ.

$$\Delta J|_{\xi_i}^{\xi_{i+1}} = \left[\mu(t) + \frac{m(0)}{m_0} a \right]_{t_i}^{t_{i+1}} \Delta t \qquad (19)$$

The time-weighting parameter a is set as 0.5 for all aircraft types to demonstrate a reasonable trade-off between fuel consumption and flight time. The value $a = 0.5$ corresponds

Table 3: Number of flights per aircraft type.

A/C type	Haneda/Narita airport		The other airports	
	Number of flights	Rate [%]	Number of flights	Rate [%]
Type-A	321	69	145	31
Type-B	231	79	60	21
Type-C	149	96	6	4
Type-D	96	55	79	45

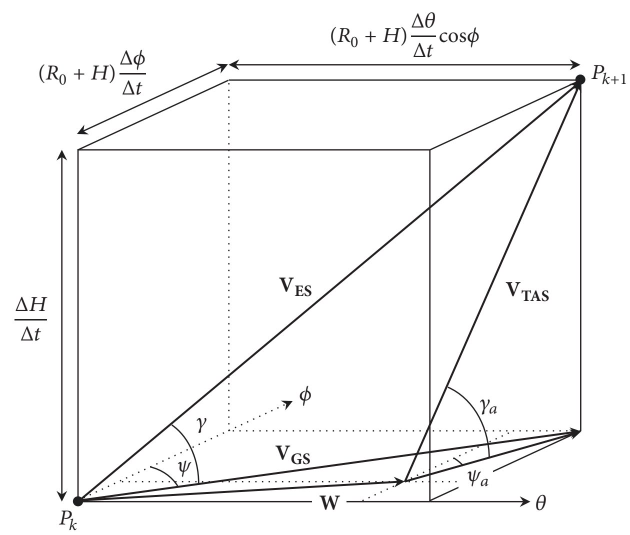

Figure 5: Definition of velocity vectors and angles in a calculation grid.

to $CI = 40$ following (17). Further, $\mathbf{x}$ and $\mathbf{u}$ are the state variable vector and control variable vector, respectively.

$$\mathbf{x} = [\xi, H, V]^{\mathrm{T}} \tag{20}$$

$$\mathbf{u} = [\psi_a, \gamma_a, T]^{\mathrm{T}} \tag{21}$$

As seen from (19), time and thrust, which is one of the control variables, are required for calculating the objective function value between the neighboring stages. Figure 5 illustrates the definition of velocity vectors and angles in a calculation grid. Earth speed $\mathbf{V_{ES}}$ is defined as the inertial velocity relative to the Earth. As all the four variable values ξ, η, H, and V are given at each grid point, four unknown quantities, namely, the three control variables and time, can be obtained by solving (1) to (4) simultaneously.

From (1) and (2) or the geometric relationship shown in Figure 5, time Δt can be gained by solving the quadratic equation

$$c_2 \Delta t^2 + c_1 \Delta t + c_0 = 0 \tag{22}$$

where the coefficients are as shown below.

$$c_2 = V_{TAS}^2 - \left(W_x^2 + W_y^2\right) \tag{23}$$

$$c_1 = 2\left(R_0 + H\right)\left[W_x \Delta\theta \cos\phi + W_y \Delta\phi\right] \tag{24}$$

$$c_0 = -\left(R_0 + H\right)^2 \left(\Delta\theta^2 \cos^2\phi + \Delta\phi^2\right) - \Delta H^2 \tag{25}$$

Once Δt is determined, the remaining three control variables can be obtained.

$$\psi_a = \tan^{-1} \frac{\left(R_0 + H\right)\Delta\theta\cos\phi - W_x \Delta t}{\left(R_0 + H\right)\Delta\phi - W_y \Delta t} \tag{26}$$

$$\gamma_a = \sin^{-1} \frac{\Delta H}{V_{TAS}\Delta t} \tag{27}$$

$$T = m\frac{\Delta V_{TAS}}{\Delta t} + D + mg\sin\gamma_a + m\frac{\Delta W}{\Delta t}\cos\gamma_a \tag{28}$$

References [14, 15] also explain how DP is applied to this four-dimensional trajectory optimization problem.

4. Results of Potential Benefits Analysis

Operational efficiency is quantified by comparing the optimized and original values in terms of flight fuel consumption, flight distance, and flight time. Achievable potential benefits are statistically evaluated by plotting these results.

4.1. Statistic Evaluation of Operational Efficiency. Operational efficiency is evaluated statistically by comparing the optimized and the original flights. Figures 6 and 7 plot the difference in flight fuel consumption and flight distance of all object flights on the axis of flight time difference. These values indicate the difference in optimized values from original values; hence, the smaller these values are, the greater benefits the flight cases potentially have. Figure 6 shows that fuel consumption differences for Type-A, Type-B, and Type-C widely vary in the range of approximately −1700 [kg] to −50 [kg]. In Type-D, most of the fuel consumption difference values are over −400 [kg]. Table 3 lists the number of flights using Haneda or Narita Airport and the other airports. Haneda Airport (Tokyo International Airport) and Narita International Airport are designated as congested airports in Japan.

In all, 45% of the domestic flights operated by the aircraft Type-D used the other airports that were not as congested as Haneda or Narita Airport. Therefore, efficiency deterioration for Type-D is considered to be suppressed to some extent. Aircraft Type-B and Type-C are categorized as middle class, whereas Type-A and Type-D are small-class aircraft. Moreover, for Type-B and Type-C, the rates of Haneda/Narita flights are higher, as summarized in Table 3. These two reasons indicate that fuel efficiency of aircraft Type-B and Type-C deteriorated to a greater extent than that of Type-A and Type-D. Table 4 lists the average difference of

Table 4: Average of difference values for each aircraft type.

A/C type	Flight time difference [s]	Fuel consumption difference [kg]	Flight distance difference [km]
Type-A	+86	−290	−20.3
Type-B	+20	−337	−20.5
Type-C	−74	−385	−20.0
Type-D	+24	−234	−17.8
All	+14	−312	−19.7

flight time, fuel consumption, and flight distance between the original and the optimized flight for each aircraft type. Fuel consumption difference for Type-B and Type-C is −337 and −385 on average, respectively. Positive correlation between distance and time as seen in Figure 7 explains that the selected speed does not differ for each aircraft type.

Figures 8 and 9 show the results for Type-A. These results were extracted from the values plotted in Figures 6 and 7. The arrival and departure flights for Haneda Airport and for Narita Airport are plotted by differently colored markers. Table 5 lists the average values as done in Table 4. Arrivals to Haneda and Narita Airports have much more potential benefit in terms of fuel consumption than departure from Haneda Airport. In Figure 9, the average points for arrival at Haneda (+34 [s], −31.5 [km]) and arrival at Narita (−38 [s], −44.9 [km]) are located at the lower left of the average point for departure from Haneda (+149 [s], −8.8 [km]) and departure from Narita (+77[s], -22.0[km]). This means that arrivals at Haneda and Narita require longer distance with longer flight time than departures from Haneda and Narita. Flight distance and flight time extension, consequently, affect fuel consumption. Figure 10 shows pressure altitude, CAS, fuel flow, and flight path of departure flights from Haneda Airport. Figure 11 plots the same quantities for arrival flights to Haneda Airport. Original and optimal flights are depicted by blue solid lines and red chain lines, respectively. Pressure altitude is plotted with the normalized flight distance. CAS and fuel flow are plotted with the normalized flight time. For both original and optimal flights, distance and time are normalized by the final values of distance and time of the original flights. Black circle markers show the end points of the optimal flights. In both figures, in the original cases, there was a tendency to cruise at lower altitude, whereas the optimal flights were made at comparatively higher cruise altitudes. In the altitude graph shown in Figure 10, the flight distance of the optimal flights is mostly the same as the distance of the original flights; however, the optimal CAS is lower than the original values. Therefore, most of the optimal flights take longer time than original flights. On the other hand, in Figure 11, the normalized flight distance of the optimal flights varies in the range of 0.7 to 1. This means that in the original cases, the flight is longer than in the optimal cases; therefore, the normalized flight time of the optimal flights varies around 1 though the optimal flights similarly select lower CAS. The relationships among CAS, flight distance, and flight time explain why the flight time difference for Haneda departure has a larger average than that of Haneda arrival.

The fuel flow graph shows that fuel consumption can be reduced for both arrival and departure flights. It is assumed that the inefficient flights among the Haneda arrivals and Narita arrivals are caused by "radar-vectored" paths instructed by air traffic controllers to adjust the arrival time and sequencing. At Haneda and Narita airports, this radar vector control is often done to handle the heavy traffic inbound to these airports. These results emphasize that serious efficiency deterioration occurs in the arrival flights to Haneda and Narita airports. Such detoured paths which cause deterioration in operational efficiency are introduced in the next section. As seen from Figure 8, over 800 [kg] of fuel can be saved with larger differences in flight time but with smaller differences in flight distance in some cases. It is assumed that, in the flights, the aircraft flew at lower altitudes with higher airspeed. The optimal cruise altitude and velocity were determined by the specific range (SR), which is the achievable cruise range per unit mass of fuel consumption as shown in

$$SR = \frac{V}{\mu} = \frac{V}{c_{TSFC}T} \tag{29}$$

where V is the true airspeed; T is the thrust; and c_{TSFC} is the thrust-specific fuel consumption which indicates the fuel mass per unit thrust per unit time. Figure 12 shows an example of the SR diagram plotted in the flight envelop of the typical jet passenger aircraft, as calculated by using the BADA aircraft performance model. The maximum SR is achieved at the maximum Mach number of 0.87 and the maximum operating altitude of 43,100 [ft]. This optimal cruise point generally exists at a higher altitude and lower equivalent airspeed (EAS). Therefore, if the aircraft flies at the nonoptimal cruise point such as lower altitude and higher EAS, the required fuel mass increases in spite of the lower effect of radar-vectoring.

These characteristic flights are explained in the next section.

4.2. An Example of Characteristic Flight. Two types of characteristic flights extracted from the statistic evaluation results are introduced in this section. Figure 13 shows 23 main airports in Japan as designated by JCAB.

(1) The Inefficient Case with Longer Flight Time. Figure 14 shows the flight paths of the 43 cases that consume more than 600 [kg] of fuel with longer flight times compared with the optimal flights. These cases are extracted from all the object types, A to D. Table 6 presents a breakdown of these flight routes. Here, 81% of the flights arrive at Haneda or Narita Airport. Airports included in the category "Others" are New Chitose, Chubu International, Kansai International, Fukuoka, and Naha Airports.

It is observed that many flights from west Japan follow winding paths in the southwest area of Haneda Airport.

Flights from Komatsu Airport also fly longer distances by merging at the intermediate point of those flights from the west. Additionally, the following three tendencies in flight path extension can be observed.

Table 5: Average of difference values for each route type (Type-A).

Route type	Flight time difference [s]	Fuel consumption difference [kg]	Flight distance difference [km]
HND arrival	+34	−314	−31.5
NRT arrival	−38	−391	−44.9
HND departure	+149	−255	−8.8
NRT departure	+77	−303	−22.0
Others	+109	−276	−15.4

Table 6: Breakdown of 43 long flights.

	Haneda arrival	Narita arrival	Haneda departure	Others
Type-A	1	1	1	0
Type-B	18	0	0	5
Type-C	13	0	2	0
Type-D	0	2	0	0
Total	32	3	3	5

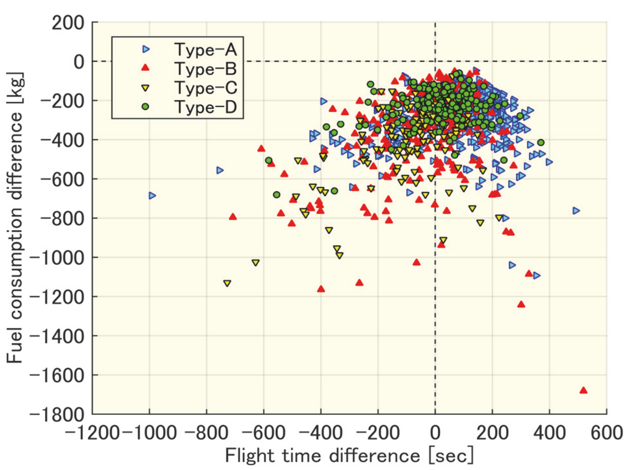

Figure 6: Fuel difference of the optimal trajectories relative to the original flights (1087 cases).

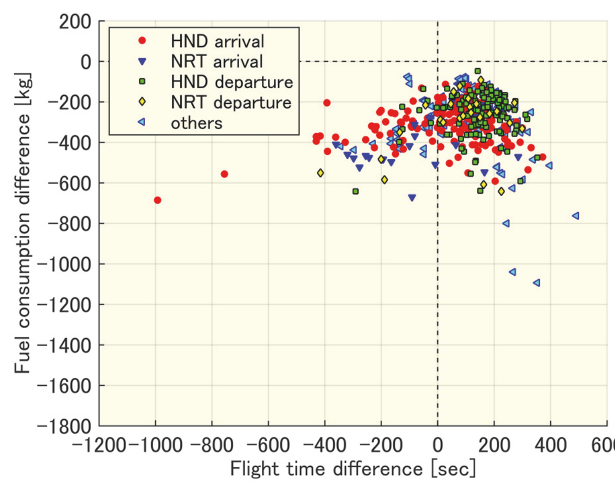

Figure 8: Fuel difference of the optimal trajectories relative to the original flights (Type-A).

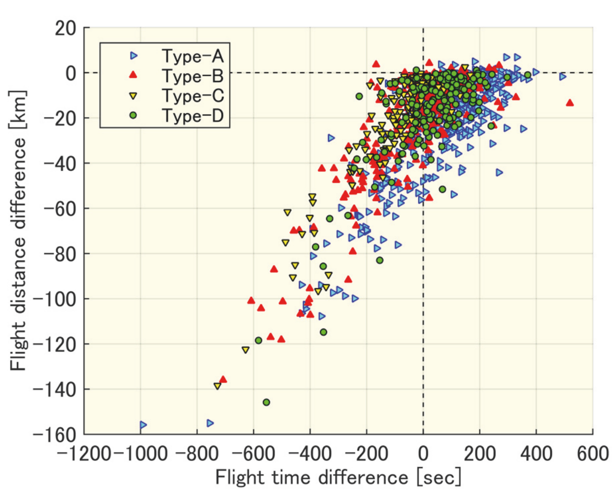

Figure 7: Flight distance difference of the optimal trajectories relative to the original flights (1087 cases).

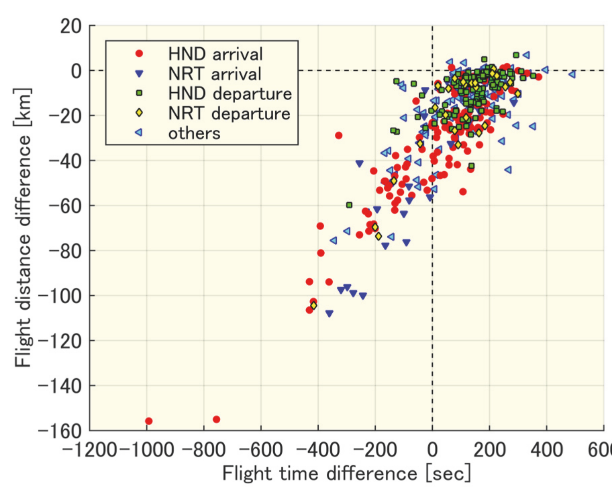

Figure 9: Flight distance difference of the optimal trajectories relative to the original flights (Type-A).

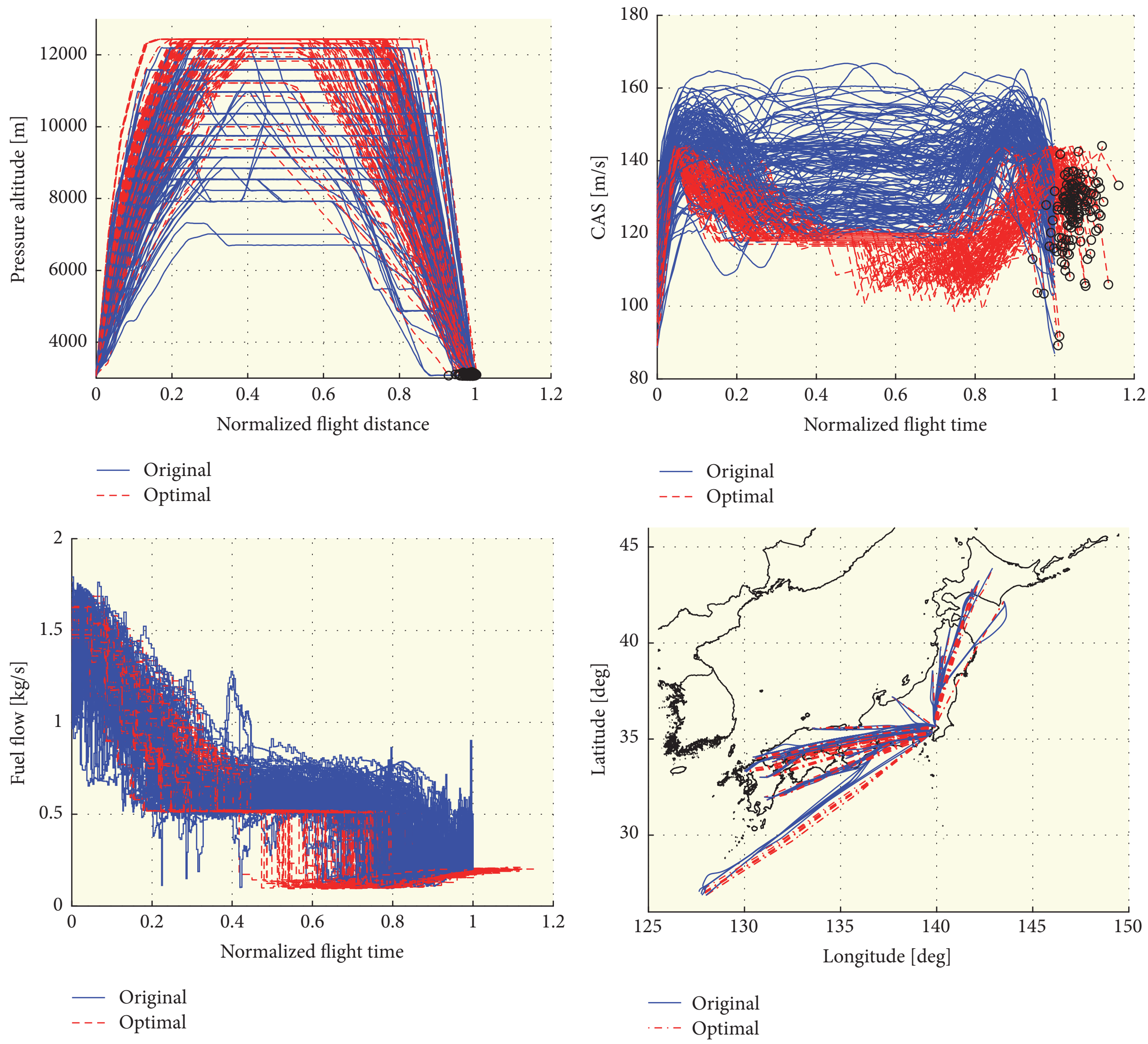

Figure 10: Pressure altitude, CAS, fuel flow, and flight path of the original and optimal departure flights from Haneda Airport.

(a) Arrival flights from Toyama Airport are greatly detoured so as to fly in the northern part of the optimal route.

(b) The flights inbound to or outbound from Narita Airport avoid the congested area caused by the arrival flights to Haneda Airport.

(c) Arrival flights to Kansai International Airport from New Chitose Airport also fly along a significantly detoured path.

(2) The Inefficient Case by the Nonoptimal Cruise. Figure 15 indicates the flight path, pressure altitude, CAS, Mach number, and fuel flow of the cases that satisfy the following conditions:

(i) aircraft Type-A,

(ii) flight distance difference between 0 and −30 [km],

(iii) fuel savings greater than 600 [kg],

(iv) positive flight time difference.

For a fuel-efficient long-range flight, generally, higher altitude and lower EAS are selected to maximize the range per unit mass of fuel consumption, as explained in Section 4.1. In spite of the fact that the flight covers distances greater than a certain level, the flight is made at a lower altitude with higher CAS than the optimal altitude and CAS in the cases. Although significant difference cannot be seen in the cruise Mach number, the CAS of the original flight is higher than that of the optimal one because of the lower cruise altitude. Therefore, the cruise fuel flow of the original flight is approximately 1.5 times the optimal value. Consequently, in the original flights, flight time could have been saved by flying at higher airspeed; on the other hand, fuel consumption dramatically increased by flying at a nonoptimal cruise point. Table 7 lists the difference in the fuel consumption of these flights.

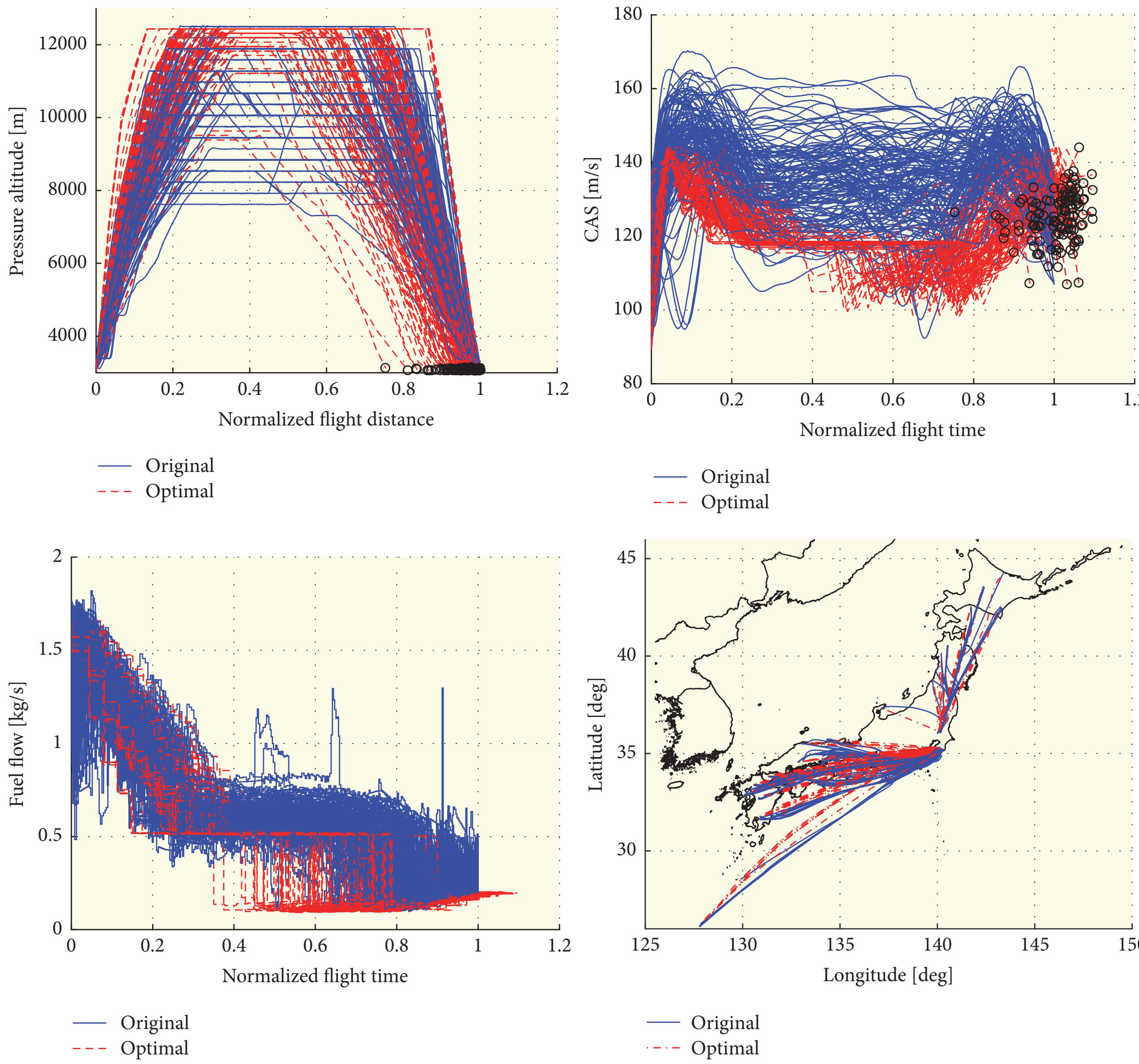

FIGURE 11: Pressure altitude, CAS, fuel flow, and flight path of the original and optimal arrival flights to Haneda Airport.

TABLE 7: Inefficient cases flying at the nonoptimal cruise point.

Route		Fuel consumption difference [kg]
Departure airport	Arrival airport	
Haneda	Kumamoto	−639
Naha	Chubu International	−1093
Narita	Fukuoka	−641
New Chitose	Chubu International	−762
Naha	Fukuoka	−626
Narita	New Chitose	−609

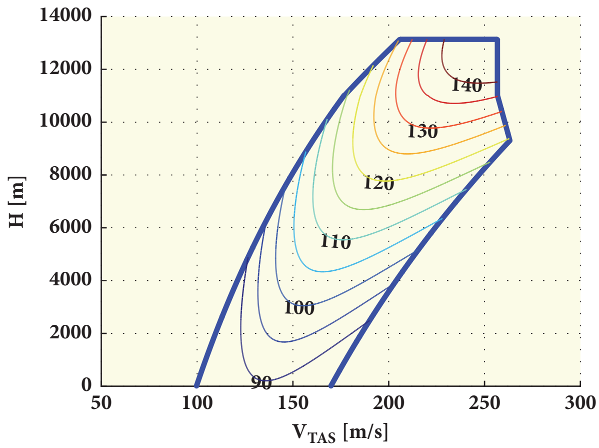

FIGURE 12: Specific range (SR [m/kg]) of a jet passenger aircraft.

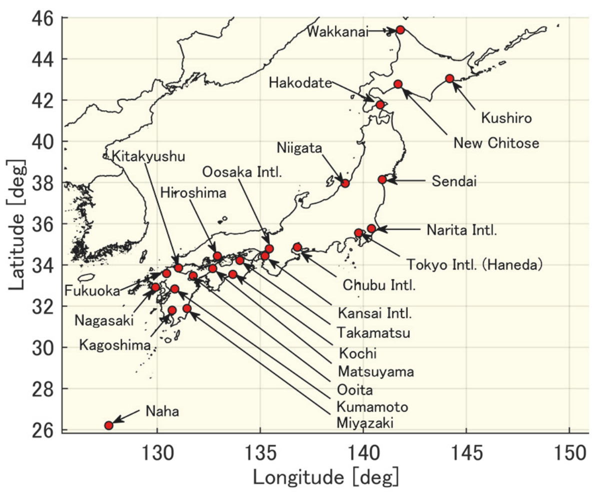

FIGURE 13: Main airports in Japan.

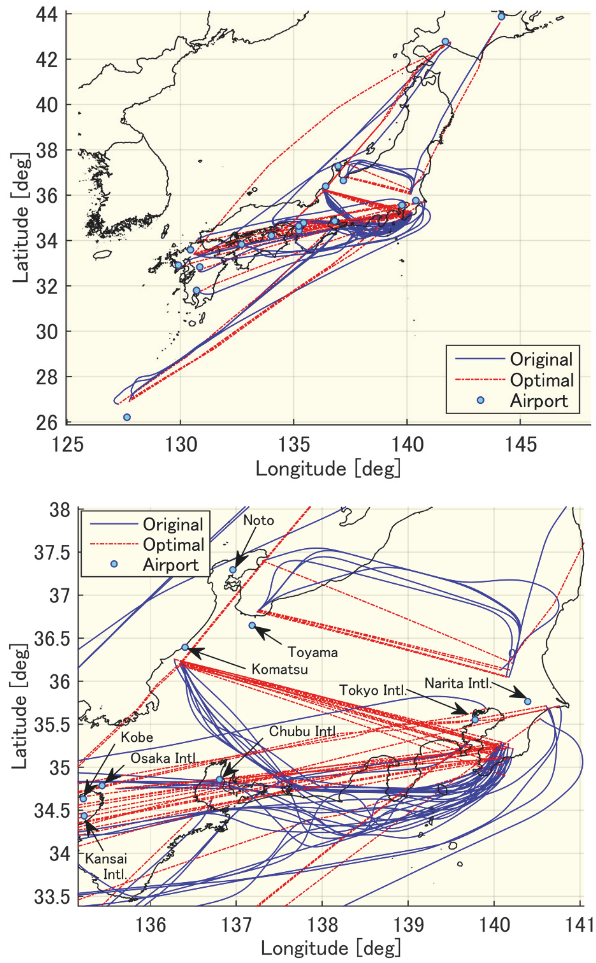

FIGURE 14: Flight path with long detour (all aircraft types); below figure is zoomed.

5. Conclusion

In this research, the operational efficiency of 1087 flights, which is about one-third of a day's domestic flights in Japan, was evaluated by comparing the optimized flight fuel consumption, flight distance, and flight time with the original values. Flight parameter estimation and four-dimensional flight trajectory optimization were applied to CARATS Open Data for calculating the fuel consumption. Half of the major four types of domestic flights were categorized as middle class, and the rest were small class; therefore, the weighting parameter of the performance index was modified to avoid the time adjustment to be affected by the scales of the aircraft.

The plotted results for all 1087 cases indicated that efficiency deterioration is remarkable in the arrival flights to Haneda and Narita Airports. This is caused by an increase in flight distance to control the arrival time and sequence manually or to avoid the congested area.

The results for Type-A aircraft were extracted from all the results to discuss characteristic flights. The major factors that might lead to efficiency deterioration are summarized below:

(1) flight distance extension,

(2) cruise at a nonoptimal point.

With regard to the first factor, there are unavoidable problems, such as the limited area for military training or noise reduction over residential areas; however, it is possible to improve efficiency in the congested areas for the arrivals at Haneda and Narita Airports by introducing an arrival management system or automated air traffic control system. The reason for efficiency deterioration by the second factor should be investigated more carefully. This type of flight is often observed in long-distance routes in Japanese domestic flights. When avoiding conflicts with other aircraft, for example, it is enough to change the altitude only in the corresponding area. The reason why some cases of long-distance flights are operated at lower cruise altitudes must be clarified.

This research has revealed the potential benefits of the current airspace, assuming that all aircraft can fly in a manner to maximize their performance under the concept of TBO. The obtained statistical information is necessary for realizing a more efficient air traffic system. It is expected that these results will be of assistance in discussing and proposing new measures for the future air traffic system.

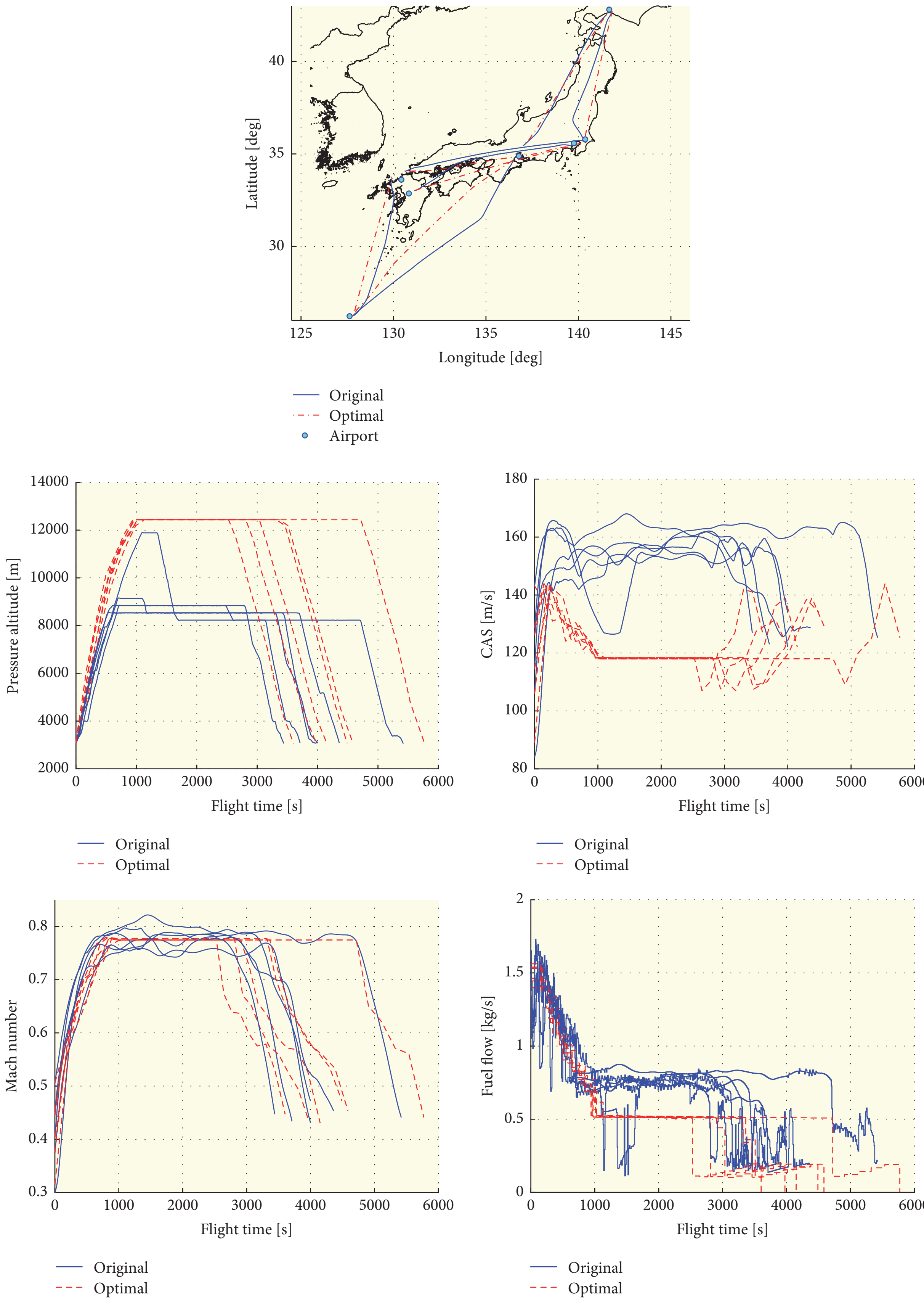

Figure 15: Flight state information of the nonoptimal cruise cases.

Nomenclature

a: Time-weighting parameter
c, C: Coefficient, direct operating cost
D: Drag
g: Gravity acceleration
H: Altitude
J: Objective function
L: Lift
m: Mass of aircraft
M: Mach number
S: Wing reference area
t: Time
T: Thrust
$\mathbf{u}$: Control variable vector
$V, \mathbf{V}$: Velocity, velocity vector
$W, \mathbf{W}$: Wind velocity, wind velocity vector
x: Longitudinal direction
$\mathbf{x}$: State variable vector
y: Latitudinal direction
γ: Flight path climb angle
η: Lateral deviation angle from great-circle
θ: Longitude
μ: Fuel flow
ξ: Great-circle angle
ρ: Air density
ϕ: Latitude
ψ: Flight path heading angle.

Disclosure

This research was presented in the Asia-Pacific International Symposium on Aerospace Technology (APISAT) held in Japan in 2016.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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