FEASIBILITY STUDY ON OPERATIONAL FLIGHT PLANS ADAPTED FOR TRAJECTORY BASED OPERATION

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Abstract

Trajectory Based Operation is a measure that enables improvement of operational efficiency even in increase of air traffic demands. In TBO, air traffic flow should be controlled so as each flight can fly as scheduled by flight plans, therefore, the flight plans must be made considering adaptability to the trajectory-based air traffic control. This research proposes an optimal flight plan which can include sufficient buffer of adjustable flight time required for traffic control in TBO. One month's data of flight plan in actual operations are analyzed in terms of adjustable flight time and fuel consumption using a trajectory optimization tool developed by the authors. The flight times of obtained optimal trajectories are compared with that of the flight plans. The maximum time difference of 300[s] with standard deviation's range of 80[s] were obtained for the 188 flight plans' data. Comparison between the flight plans and the actual flights indicated that 350[s] of adjustable flight time is required in the current operation. The numerical results revealed that the optimal trajectories have a potential to be effectively used as the flight plans in the TBO while guaranteeing the required buffer of adjustable flight time without increasing fuel consumption.

Keywords: trajectory-based operation, operational efficiency, trajectory optimization, operational flight plan

1. Introduction

Trajectory Based Operation (TBO) is one of the measures which can contribute to operational efficiency improvement while handling increase of air traffic demands. Flight trajectory should be properly managed in terms of both fuel efficiency and traffic throughput. Operational Flight Plans (OFPs) created by airline companies are important in that they are used as references of actual flight operations and influence on the operational efficiency. However, actual flight operations today are not always done following the current OFPs due to air traffic controllers' instructions or pilots' intentions; OFPs of Japanese domestic flights are not yet optimized from the viewpoints of traffic efficiency even though they are developed to be adaptable to Air Traffic Control (ATC). The OFPs should be well-adjusted so as to fit with appropriate ways of Air Traffic Management also in the future TBO. The efficiency and optimization of the OFP has been a subject of interest also in previous studies. For instance, the impact of OFP route selection on delay time and potential conflicts has been analyzed [1]. Additionally, supposing recent improvements in cockpit connectivity, the real-time optimization of flight trajectories and its associated efficiency improvements have been investigated [2]. Furthermore, optimal OFP trajectories in the context of Free Route Airspace have been demonstrated [3]. The validity of the planned fuel quantity in the flight plan has also been analyzed [4]. However, these studies have not addressed the capacity to accommodate potential ATC instructions included in the OFP. In this study, we aim to clarify the feasibility of constructing OFPs that can be adoptable to air traffic control instructions with sufficient buffer of adjustable flight time without increasing required fuel consumption. To this end, first, by comparing the OFP trajectories with the fuel-optimal trajectories which have several flight times, we clarify how the OFP achieves adaptability to air traffic control instructions in the context of futuristic TBO. Subsequently, we analyze the fuel-optimal trajectories that maintain the sufficient buffer of adjustable flight time.

Previous studies have investigated the maximization of the adjustable flight time buffer through descent route optimization [5, 6] and optimal flight control [7, 8]. This study expands the scope of the target airspace to a broader region, extending to the first waypoint where air traffic control for arrival flights is initiated. This expansion is expected to result in a proposal for more valuable OFPs.

Figure 1 shows the actual flight tracks of the air route from Fukuoka Airport to Tokyo International Airport (called Haneda Airport hereafter), which often has the heaviest traffic in Japanese domestic routes, in certain two days in 2019. The flight tracks were extracted from CARATS Open Data maintained by Japan Civil Aviation Bureau (JCAB) [9, 10]. Many flights were radar-vectored after passing the waypoint FLUTE by the air traffic controllers' instructions. The traffic arriving from west side is controlled still using radar vector for separation and queuing, even though the Point Merge System (PMS) has been introduced in the Standard Instrument Arrival (STAR) of Haneda Airport. The radar-vectored flights are often instructed level off during descent, and such the flights are exposed to be in a possibility of higher impact on fuel consumption. The radar vector also has a problem that it needs wide airspace, therefore, the other traffic must avoid the airspace. In fact, the arrival flights to Narita International Airport, which locates at a distance of about 60km east from Haneda Airport, avoids the airspace where the radar vector control is conducted for the arrival flights to Haneda Airport. Arrival control is preferable to be performed in vertical plane first. Ensuring a buffer for flight time adjustment while minimizing impact on fuel consumption is possible by optimizing vertical path including location of Top of Descent (TOD) points, and speed, not including horizontal path stretch.

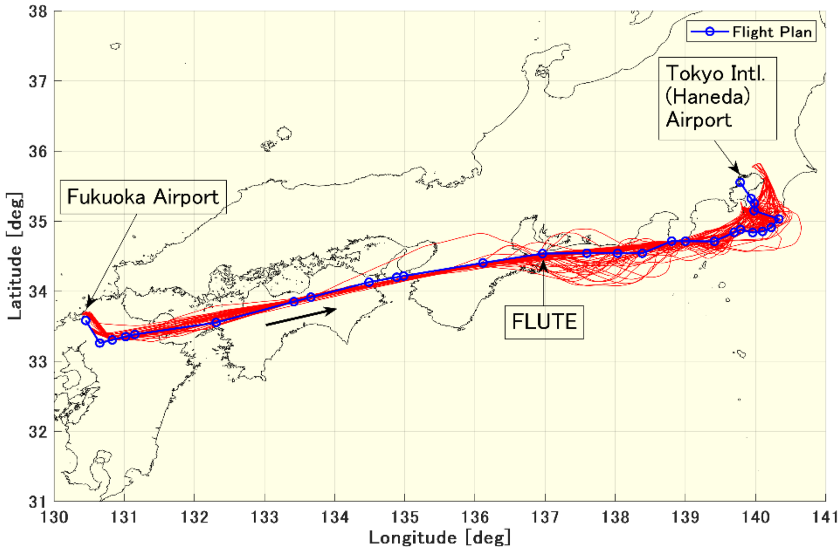

Figure 1 – Actual 108 flight tracks from Fukuoka Airport to Haneda Airport.
(Extracted from certain two days' data in CARATS Open Data 2019 [10].)

The blue line with circle marker in Figure 1 is a flight plan's route picked from the provided OFP data. The route is determined by connecting RNAV (Area Navigation) route with SID (Standard Instrument Departure) and STAR. Although the route is approximately optimal, the vertical path and speed are not completely designed considering a buffer of flight time adjustment for arrival control. The current flight plans have plenty of scope for improvement, if looking ahead that they will be effectively used in TBO. This research proposes application of the optimal trajectories with sufficient buffer of flight time adjustment as the flight plans suitable for future TBO.

2. Data used in the Analysis

2.1 Operational Flight Plan (OFP) Data

The OFP data provided by Japan Airlines Co., Ltd. is used. This OFP data is created by CAE's Flight Plan Manager [11] which is used in the actual operations of Japan Airlines. In the OFP data, waypoints' names and coordinates, barometric altitude, ground speed and airspeed information, average wind velocity and temperature between waypoints, flight time between waypoints called Zone Time (ZTM), and weight of remaining fuel are included. These data used in this research are the latest ones created just before the actual flights depart. The number of flights where the OFP data was provided are listed in Table 1. In total, the number of provided OFP data is 511.

Table 1 – The flights where the OFP data was provided.

Flight route	Fukuoka Airport to Haneda Airport					
Aircraft type	A359	B772	B763	B788	B738	Total
Number of flights	298	37	85	60	31	511
Percentage	58.3	7.2	16.6	11.7	6.1	100
Period	6/1/2022～6/30/2022 (after the global COVID-19 pandemic)					

In this paper, the flights from Fukuoka Airport to Haneda Airport were analyzed. Because two of these flights were the unscheduled flights such as a cargo or charter flight, they were excluded from the analysis object. The total number of the available OFP data was 509.

2.2 Weight Data

Since the trajectory optimization calculation needs aircraft weight value as one of the initial conditions, the two types of data related to aircraft weight were also provided: the actual zero-fuel (ACTZF) weight including both actual freight's and passengers' weight, and OFP's take-off fuel (PLNTOF) weight. Summation of these values were used as take-off weight in the analysis.

$$m_{\mathrm{TO}} = m_{\mathrm{ACTZF}} + m_{\mathrm{PLNTOF}} \tag{1}$$

2.3 Meteorological Data

In the trajectory optimization calculation considering practical applications, meteorological condition must be considered in each flight. Meteorological Grid Point Value (GPV) data released by Japan Meteorological Agency (JMA) data [12] is used in this analysis. Wind velocity (meridional and zonal components), atmospheric temperature, and geopotential altitude are stored at each barometric surface in GPV format. Global Spectral Model (GSM) was used to reduce computational load this time.

3. Methodology of Analysis via Flight Trajectory Optimization

3.1 Overview of Analysis Method

Candidate trajectories for the future flight plans used in the TBO are calculated by flight trajectory optimization. The optimal trajectories with different flight times are prepared for the candidates. The simple fuel-minimal trajectory without considering flight time is included in the candidates. The flight times and fuel consumption of the candidate trajectories are compared to that of the current flight plans to examine feasibility of the buffer of adjustable flight time.

3.2 Flight Trajectory Optimization by Dynamic Programming

3.2.1 Performance Index

The performance index to be minimized in the optimization calculation is defined as Eq. (2). Direct Operating Cost (DOC) which is determined by combination of fuel consumption and flight time is used as the performance index.

$$J = \int_{t_0}^{t_f} [\mu(t) + a] \mathrm{d}t \tag{2}$$

Here, μ [kg/s] is the fuel flow and a is the weighting parameter that is used to adjust the flight time. The trajectory optimization calculation searches the fuel minimal trajectory from a set of feasible trajectories for each given value of the parameter a [kg/s]. Consequently, the optimal trajectories which have various flight times can be obtained as a trade-off between fuel consumption and flight time. The time weighting parameter is closely related with Cost Index (CI) used in the actual flight operations. The performance index which equals to the cost of flight is described with the unit of dollars,

$$J_{\mathrm{dollars}} = \int_{t_0}^{t_f} \left[\frac{1}{100} \frac{C_{fuel}}{0.4536} \mu(t) + \frac{C_{time}}{3600} \right] \mathrm{d}t, \tag{3}$$

where C_{fuel} is the fuel cost in [cent/lbs], and C_{time} is the time cost in [dollars/hour] (for Boeing aircraft). Because CI is defined as the time cost per fuel cost, the following relationship can be established between the parameter a in Eq. (2) and CI, using Eqs. (2) and (3).

$$\mathrm{CI}_{\mathrm{Boeing}}[100\mathrm{lbs/hour}] = \frac{C_{time}[\mathrm{dollars/hour}]}{C_{fuel}[\mathrm{cent/lbs}]} = 79.37a[\mathrm{kg/s}] \tag{4}$$

For Airbus aircraft, the following relationship is established [13].

$$\mathrm{CI}_{\mathrm{Airbus}}[\mathrm{kg/min}] = \frac{C_{time}[\mathrm{dollars/min}]}{C_{fuel}[\mathrm{dollars/kg}]} = 60a[\mathrm{kg/s}] \tag{5}$$

Figure 2 explains trade-off between fuel consumption and flight time. The value of CI or the weighting parameter a is equivalent to the slope of tangent to the feasible solutions' boundary, therefore, a Pareto front is formed by the optimal solutions for various weighting parameters. In this manner, cost index represents a free parameter for each performance index to be optimized.

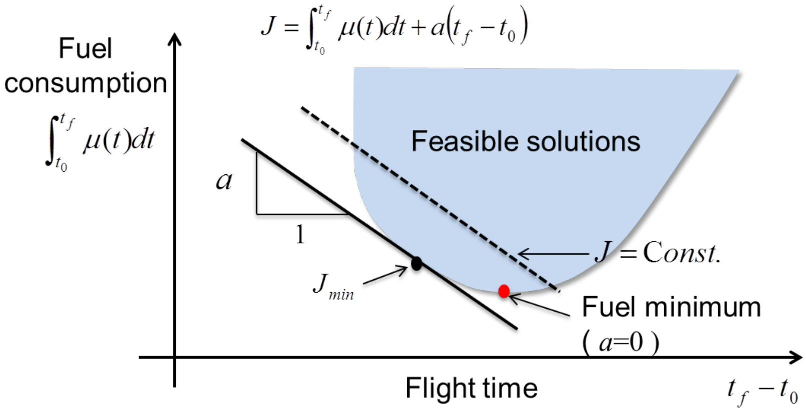

Figure 2 – Relationship between feasible solutions and time weighting parameter a

3.2.2 Governing Equations

Aircraft motion is described by three-degree-of-freedom (3DOF) governing equations defined with point mass approximation. The state variables are calibrated airspeed CAS and barometric altitude, while thrust and flight path climb angle which govern aircraft's longitudinal motion are adopted as the control inputs with the assumption of quasi-steady flight. The governing equations are given in five Eqs. (6) to (10).

$$\frac{\mathrm{d}X}{\mathrm{d}t} = V_{TAS} \cos\gamma + V_W \tag{6}$$

$$\frac{\mathrm{d}H}{\mathrm{d}t} = V_{TAS} \sin\gamma \tag{7}$$

$$m\frac{\mathrm{d}V_{TAS}}{\mathrm{d}t} = T - D - mg\sin\gamma_a - m\frac{\mathrm{d}V_W}{\mathrm{d}t}\cos\gamma_a \tag{8}$$

$$m\frac{\mathrm{d}\gamma}{\mathrm{d}t} = L + m\frac{\mathrm{d}V_W}{\mathrm{d}t}\sin\gamma_a - mg\cos\gamma_a = 0 \tag{9}$$

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -\mu \tag{10}$$

$$L = \frac{1}{2}\rho V_{TAS}^2 S C_L \tag{11}$$

$$D = \frac{1}{2}\rho V_{TAS}^2 S C_D \tag{12}$$

$$C_D = C_{D0} + K C_L^2 \tag{13}$$

The value of V_{TAS} at an altitude is calculated from the value of CAS given as a state variable. Eqs. (8) and (9) are formulated considering the influence of wind velocity change in the non-inertial frame. Due to quasi-steady assumption, the time derivative of the flight path climb angle becomes zero as Eq. (9). Fuel flow μ is calculated from BADA model [14], where the aircraft performance parameters regarding aerodynamic characteristics and thrust specific fuel consumption are given in the form of Operational Performance File (OPF) for each aircraft type. Aerodynamic model, lift, drag, and their non-dimensional coefficients are expressed in Eqs. (11) to (13). The parabolic polar model in a clean configuration is used. The parasite drag coefficient C_{D0} and induced drag coefficient factor K are brought from the OPF in the BADA model.

3.2.3 Optimization Logic

Various trajectory optimization methods exist within the field of optimal control or optimization theory. This research uses dynamic programming (DP) which is classified into direct optimization methods. The optimal trajectory is determined by selecting grid points generated in a state space such that the performance index, calculated by Eq. (2), is minimized. Although DP guarantees global optimality if the calculation is performed for every feasible grid point combination, the computational load grows rapidly with an increasing number of state variables. To avoid this computational difficulty, which is known as the curse of dimensionality, the Moving Search Space DP (MS-DP) method is applied. This is one of the fast computation approaches of DP devised in the previous research [15]. In the method, the optimal solution is searched by following the idea of steepest descent method, with fewer grid points in a limited state space. The space is set around an initial guess for the first calculation. Linear lines which simply connect initial and terminal points are given as the initial guess in the optimization calculation in this research. How the initial guess is given may influence on the optimality of the obtained solution, in such a case of existing strong head wind layer.

4. Analysis Results

4.1 Analysis Object

Only the 188 of the 509 OFP data explained in the section 2.1 were analyzed. These 188 data were the flights that scheduled to land to the runway 34L or 34R of Haneda Airport. Table 2 lists the number of the analyzed OFP data for each aircraft type.

Table 2 – Number of the analyzed OFP data.

Flight route	Fukuoka Airport to 34L/34R of Haneda Airport					
Aircraft type	A359	B772	B763	B788	B738	Total
Number of flights	111	12	38	20	7	188

Figure 3 shows the actual flight tracks excluding the flights which changed the landing runway from the scheduled one, for reference. These are Automatic Dependent Surveillance Broadcast (ADS-B) data obtained from an online service, Flightradar24.com [16]. The optimization calculation was performed for the OFP data, with a condition of flying on the planned route from FLUTE to ANZAC where radar vector control was conducted for arrival traffic flow. Each flight plan’s altitude and speed were optimized on the route in terms of fuel consumption and flight time using the identical meteorological conditions and aircraft performance model. The flight times of the optimal trajectories were compared with those obtained from the OFP data from the viewpoint of adjustable flight time.

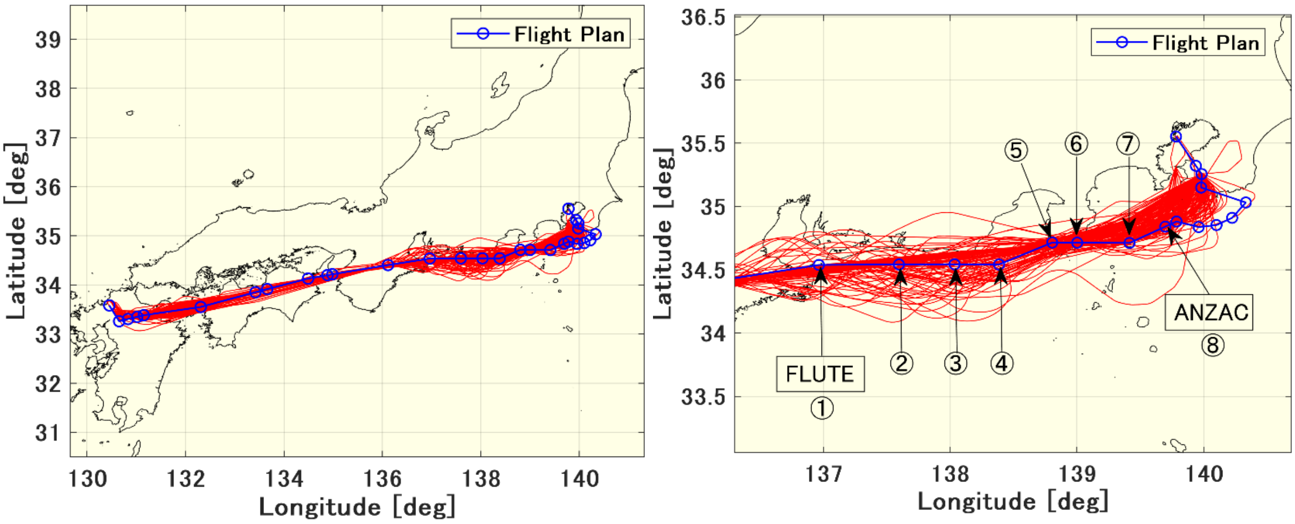

Figure 3 – Actual flight tracks inbound to 34L/34R of Haneda Airport with a flight plan's route from Fukuoka Airport to Haneda Airport of June 2022. Left: overall. Right: zoomed.

4.2 Calculation Conditions

Table 3 presents the calculation condition of the trajectory optimization. The optimization calculation was performed for the vertical plane which was set along the flight plan's route between FLUTE and ANZAC. The calculation interval was defined by dividing the flight distance into approximately 20km segments along the route. As shown in Table 3, the upper bound of the altitude was set to be the cruise altitude of the flight plan for every flight. The plan's altitude and indicated airspeed (IAS) at FLUTE were also used as the initial condition. These values were picked from the OFP data. The aircraft mass value required at the initial point can be derived by subtracting burned fuel weight in the OFP data from the takeoff weight m_{TO} denoted in Eq. (1). The altitude and IAS at the terminal point ANZAC were fixed to the values of 13,000[ft] and 230[kt] respectively, considering the restrictions on the following PMS leg [17].

The analyzed 188 flights include five types of aircraft as listed in Table 2. The corresponding performance data of BADA 3.15 was used for each aircraft type [14].

Table 3 – Calculation condition

Route	Flight plan's routes connecting FLUTE with ANZAC					
Flight distance	X_0:	0	X_f:	259 [km]	ΔX:	Approx. 20 [km]
Altitude	$H_{\min}$:	–	$H_{\max}$:	$H_{cruise\ \mathrm{OFP}}$	ΔH:	100 [m]
IAS	$V_{\min}$:	BADA reference	$V_{\max}$:	BADA reference	ΔV:	0.5 [m/s]
Initial condition	H_0:	$H_{FLUTE\ \mathrm{OFP}}$	V_0:	$V_{FLUTE\ \mathrm{OFP}}$		
Final condition	H_f:	13,000 [ft]	V_f:	230 [kt]		
Time weighting parameter	a:	$0, 1, 2, 3, 4, 5$				

4.3 Adjustable flight time buffer by optimal trajectories

Optimal trajectories were obtained for all the 188 flight plans in order to clarify the adjustable flight time buffer under the calculation condition with the given parameter a. Figure 4 shows plots of the flight time difference and fuel consumption difference between the optimal and flight plans' trajectories for each time weighting parameter. The planned flight time was obtained by summing ZTM values between FLUTE and ANZAC. The results for all the 188 flights and for each aircraft type are shown. The blue line with left axis is the time difference and the red one with right axis is the fuel consumption difference, respectively. The circle marker indicates the mean values, and the top and bottom whiskers represents the range of standard deviation. In the result of the case of $a = 5$, flight times of the optimal trajectories are approximately equal to that of the flight plans. Additionally, reduction of fuel consumption in the case of $a = 5$ is smaller compared to that in the case of $a = 0$. This indicates that the current flight plans are made with heavy account of flight time, with sufficient buffer of fuel consumption. As the parameter a takes smaller value, flight time difference becomes

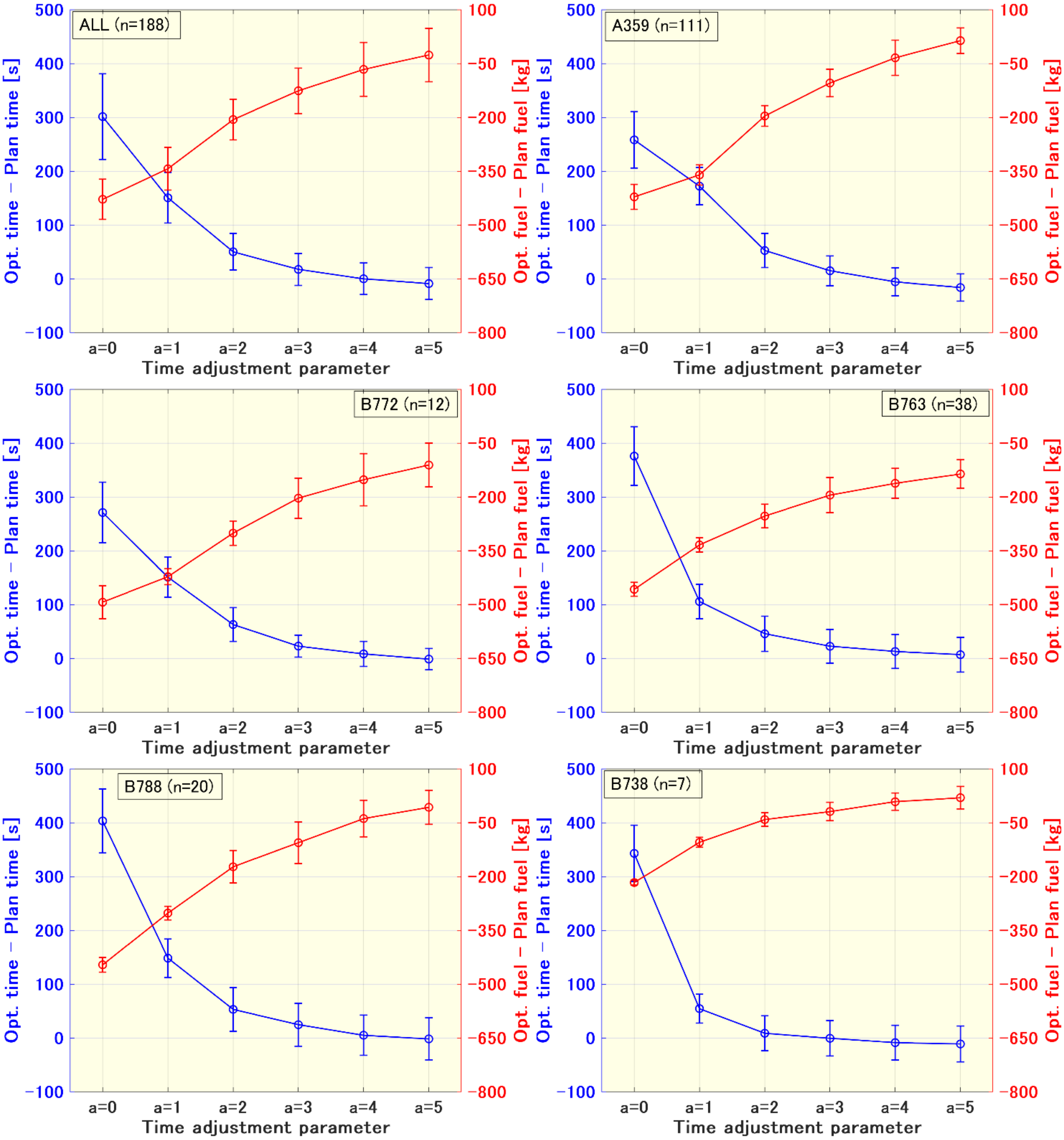

Figure 4 – Flight time difference and fuel consumption difference between the optimal and flight plans' trajectories.

larger because the flight time of the optimal trajectory becomes longer in the case. In the result for all the case of 188 flights, the mean value of flight time difference takes maximum of 300[s] in the case of $a = 0$. The reduction of fuel consumption also becomes maximum of 430[kg] in the case. Similar tendency can be seen in the result of A359 which occupies 59.0% of all the analysis object.

Figure 5 shows comparison of altitude histories between optimal and flight plans' trajectories for 111 cases of A359. The blue, green and red lines are the optimal trajectories of altitude in the case of $a = 0, 2,$ and 5. The black lines show altitude trajectories of flight plans. The TOD points move to the arrival airport side as the value of time weighting parameter increases. In the case of $a = 5$, most of the TOD points are located around waypoint #4. These TOD points are almost identical to that of the flight plans. The altitude seems not designated as 13,000[ft] at the terminal point ANZAC in the flight plans.

Figure 6 depicts the CAS histories of the optimal trajectories for the same 111 cases. In the case of $a = 0$, the CAS values widely vary compared to the other cases. This causes wider variation of flight

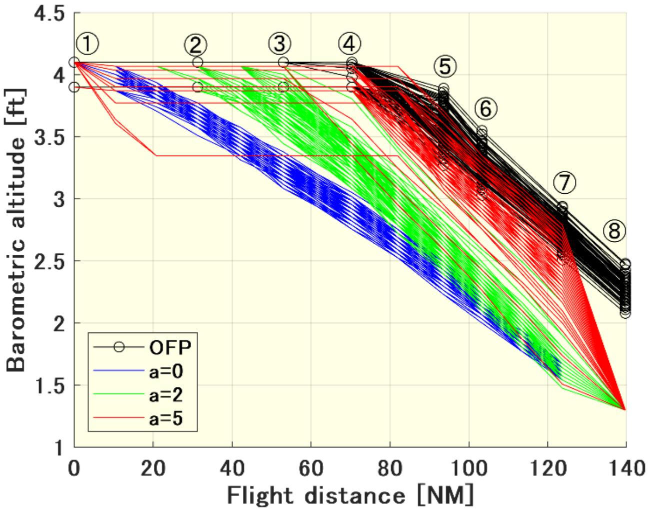

Figure 5 – Comparison of altitude trajectories.
(A359, n=111)

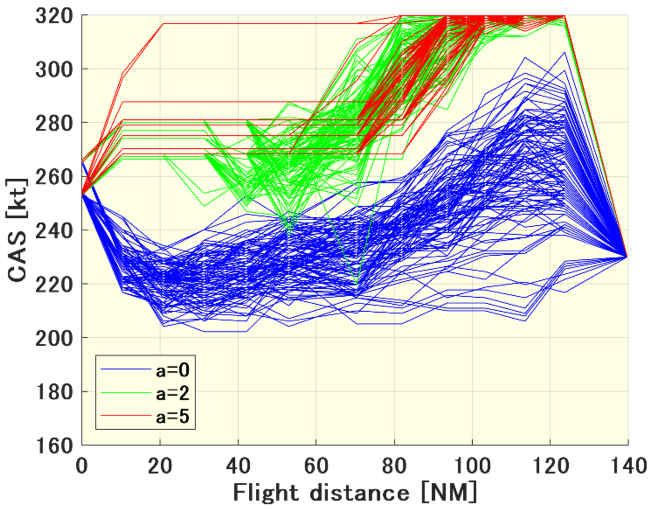

Figure 6 – Optimal trajectories of CAS.
(A359, n=111)

time difference as shown in Figure 4.

Figures 7 and 8 are the flight plan's flight time and actual flight time between FLUTE and ANZAC. On each box, the red line indicates the median, and the bottom and top edges of the box indicate the first and the third quartiles, respectively. The whiskers extend to the maximum and minimum points which don't include outliers. The outliers are plotted by plus-shaped marker symbol. Comparing plans' flight time between A359 and B738 in Figure 7, the plans' flight time seems reflect each aircraft performance. The range of planned flight time for all the cases is between 840[s] and 1140[s], and the median is 960[s].

In Figure 8, to calculate the actual flight time, the nearest points to the waypoints FLUTE and ANZAC were selected because the actual flights do not always fly over these waypoints as presented in Figure 3. The range of actual flight time for all the cases is between 920[s] and 1740[s] including outliers, and the median is 1060[s].

Flight time difference between the flight plans and the actual flights is summarized in Figure 9. The required buffer of adjustable flight time is supposed to be 350[s] to the most, except for the outlier flights.

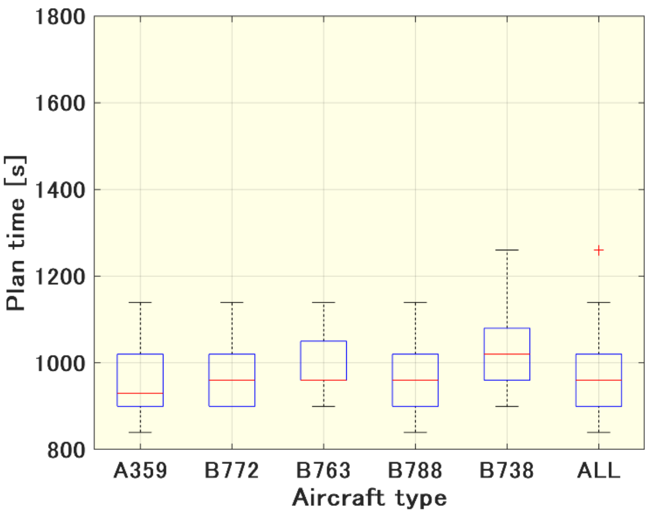

Figure 7 – Planned flight time.
(FLUTE–ANZAC)

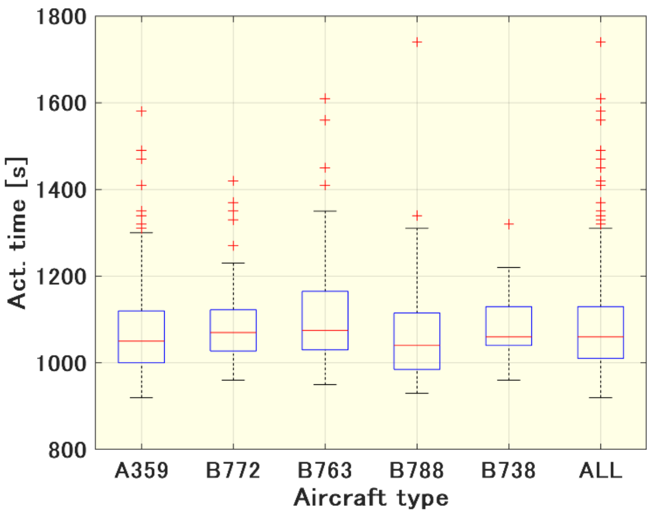

Figure 8 – Actual flight time.
(FLUTE–ANZAC)

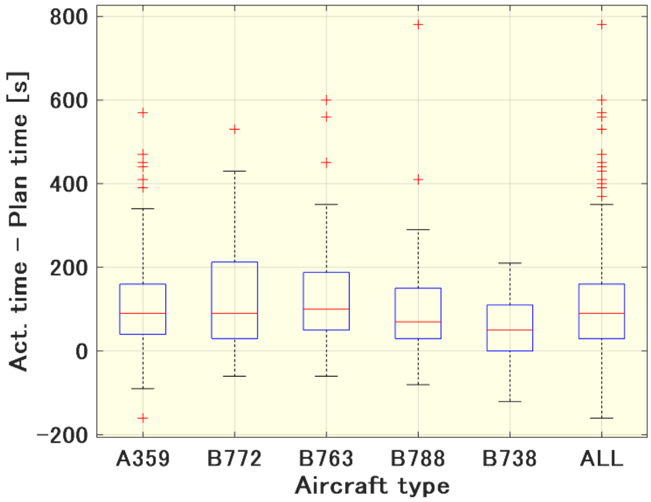

Figure 9 – Difference between the planned flight time and the actual flight time.

5. Conclusion

The operational flight plan (OFP) should be adoptable to the upcoming TBO considering both traffic throughput and fuel efficiency. In the TBO, more efficient and intelligent method of flow management and traffic control will be required for the arrival flights to a major airport. This research reconsidered the current OFPs in terms of a buffer of adjustable flight time by using the flight trajectory optimization analysis, focusing on Haneda Airport which has the heaviest traffic in Japan. The 188 OFPs which were scheduled to fly from Fukuoka Airport to the runway 34L or 34R of Haneda Airport were analyzed. The data period was one month of June in 2022 after the global pandemic of COVID-19. The optimal trajectories were calculated for these OFPs while changing the time weighting parameter in the performance index. The time difference of 300[s] with the standard deviation's range of 80[s] were obtained for the analysis target of 188 OFPs. From the result of comparison between the OFPs and the actual flights for the one month's data, the required buffer of adjustable flight time in the current operation was 350[s] to the most, without considering the outlier flights. Although the proposed method of control which will be performed only in the vertical plane is different from the currently conducted radar vector-based control, the obtained results are worth mentioning that the fuel minimal trajectories with the weighting parameter $a = 0$ have a potential to guarantee the required buffer of adjustable flight time. The proposed method for the future TBO also has a merit that fuel consumption increase does not occur in extending flight time, compared to the current way of traffic control because the control is performed only for altitude and speed without changing horizontal path. Furthermore, a possibility of reduction of loaded fuel weight can be expected.

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7. Copyright Statement

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