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# OPTIMIZATION OF AIRCRAFT FLIGHT PATHS CONSIDERING THE CONFLICTING PARAMETERS OF ECONOMY AND SAFETY

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## Abstract

Autonomous aircraft flight without a human pilot has been attracting increasing attention. One of the most important tasks is that the pilot set the flight plan (including the flight path, airspeed, and amount of fuel installed) by considering all the influencing factors. However, automatically generating an optimum flight plan corresponding to emergencies remains a significant challenge in terms of recognizing the emergency and ensuring safety both on board and on the ground. In this study, we propose a method to optimize the entire flight path while considering the conflicting parameters of economy and safety. Fuel consumption was considered the economic factor, while the comparison between the flyable distance in the loss of thrust emergency and the distance to the runways was considered the safety factor. A dynamic planning method was applied to simultaneously optimize the conflicting parameters. In the experiment, we confirmed the effectiveness of the proposed method by applying it to the Haneda-Naha route by setting different weight coefficients for the two factors. The most economical flight path obtained was very close to the shortest path (i.e., the global circle route), and the safest path was obtained close to the coastline. This relationship shows that the optimal flight path can be selected based on the considered conditions.

**Keywords:** multi-objective; flight path optimization; flight safety; emergency landing; fuel consumption

## 1. Introduction

Training pilots requires significant expense and time, and air transport demand is expected to grow again when COVID-19 has been eliminated [1]; however, the pilot shortage will be a severe problem, as it was an issue before the COVID-19 pandemic began. Autonomous flight of aircraft has been attracting attention as a solution [2, 3]. An autonomous flight system should be able to achieve all tasks during a flight as good as or better than a human pilot. There are three main tasks for a pilot: recognition of flight conditions, decisions regarding the flight plan, and flight operations. For flight condition recognition, a pilot should monitor the status of the aircraft systems, payloads, weather to the destination, facilities for aircraft operations, and aircraft flying in the vicinity. In most recent aircraft, this data is collected in various ways, and pilots can be made aware of the flight conditions in the cockpit for automatic recognition [4]. For flight operations, a pilot should control the aircraft according to the flight plan. Currently, most aircraft can fly automatically in almost all flight phases, except for taxiing on the ground, take-off and landing, and emergencies [5].

One of the most important tasks is the decision of the flight plan, in which a pilot must set the destination, flight path, altitude, and airspeed while considering all influencing factors (e.g., weather, airframe, airports, and other flights) from the perspective of comfort, punctuality, and economy, with the highest priority for safe operation. For example, suppose the aircraft cannot arrive at the destination airport because of bad weather. In that case, the pilot must decide whether to change the flight altitude to bypass the inclement weather, divert to another airport, or return to the departure airport [6]. If the aircraft cannot continue the flight safely, the pilot must immediately decide to make an emergency landing and do their best to save lives both onboard and on the ground [7]. Therefore, automatically generating an optimum flight plan corresponding to emergencies remains a significant challenge for autonomous flight systems from such viewpoints.

On the other hand, the partial implementation of free route airspace has already started [8]. In such airspace, users can freely choose their routes even under the air traffic control. The in-flight positions are determined with a high level of accuracy by using the global navigation satellite system (GNSS) and inertial reference system (IRS) and shared with ground control so that flight paths can be selected optimal routes without reference to the ATS route network. As a future scenario, free flight aims for further efficient air transportation, allowing free and direct flight. However, even so, the flight route should also be generated from various perspectives, including flight safety.

In this study, an automatic method is proposed to generate the flight path for various flight situations by simultaneously considering the flight economy (e.g., fuel consumption) and safety (e.g., emergency landing); this is achieved by formulating and solving a multi-objective path optimization problem. The base of aircraft data (BADA) [9] provided by Eurocontrol was introduced to calculate the flight characteristics. The fuel consumption was estimated from the flight conditions (flight path, altitude, and airspeed) and weather conditions (wind speed and direction) and used to evaluate the flight economy. The flyable distance in emergencies (e.g., loss of thrust emergencies) was also estimated and compared with the distance to the nearest airport to calculate the risk. We used a dynamic planning method, Dijkstra's algorithm [10], to determine the optimal flight path by minimizing the weighted linear combination of fuel consumption and flight safety risk. In experiments, we estimated the flight paths by assigning different weight coefficients to the two conditions of economy and safety and applied them to an actual route. The results demonstrated the effectiveness of the proposed method.

The contributions of this study are three-fold. (1) We propose a method for autonomous aircraft to generate flight paths by considering both safety and economic terms. (2) We created a simple function for estimating the safety risk by comparing the flyable distance in a loss of thrust emergency and the distance to the nearest runway. (3) We confirmed the relationship of the flight paths by assigning different weight coefficients of economics and safety, which helps determine the optimal flight path.

## 2. Related work

Before and during normal flights, to generate and modify the flight plan (including the flight path, airspeed, and fuel consumption), various conditions must be considered, such as the weather, arrival time, and fuel required for diversion. In emergencies, an appropriate flight plan should be generated in a short time to prevent failed landing or mitigate fatalities risks. Various studies have been conducted on both normal and emergency flight plans.

### 2.1 Normal flight plan

With the widespread use of RNAV (area navigation) systems, flying in a straight line independent of navigational aid facilities is now possible; thus, commercial aircraft can choose routes closer to the shortest large-area routes for economic efficiency [11, 12].

The priority perspectives of airline pilots in the flight route decision process are flight safety, comfort, punctuality, and economy [13]. For each of these priorities, flight path optimization methods have been proposed. For flight safety and comfort, Schilke et al. [14] and Ng et al. [15] proposed methods to optimize flight paths while avoiding bad weather conditions, such as cumulonimbus clouds and thunderstorms. Jardin et al. [16] and Bijlsma [17] proposed a method for computing minimum-time flight paths in a strong-wind environment for punctuality. Kithmal et al. [18, 19] applied a dynamic planning method to the economic efficiency optimization problem of flight paths to minimize fuel consumption with the constraint of arrival time.

Since the current aviation system achieves high reliability based on pilot involvement and responsibility, there has been little research on the flight planning function in normal conditions from the perspective of flight safety.

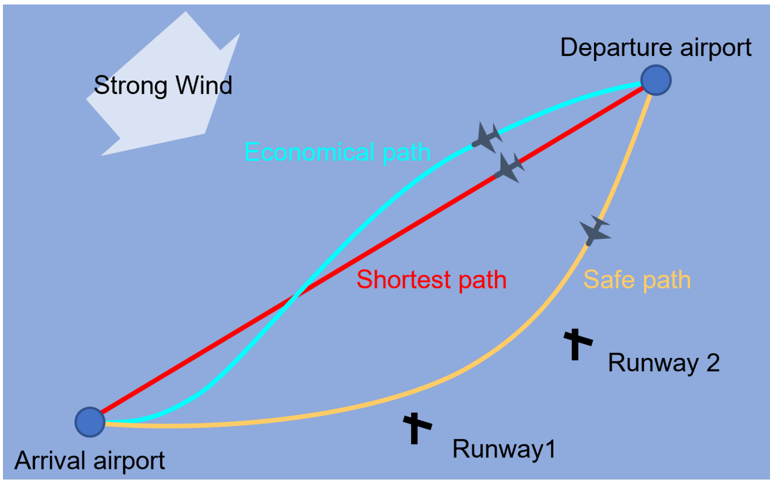



Figure 1 – Generation of flight paths considering different conditions.

### 2.2 Emergency flight plan

Much of the research on emergency flight planning has focused on emergency landing by gliding in situations where all engines are inoperative. Saswata et al. [20] and McLain et al. [21] proposed the application of Dubin's pathways, which is well known as a path-planning technique for mobile robots or planar aerial vehicles, as well as flight paths for emergency landings of fixed-wing airplanes. This approach applied to the case of US Airways Flight 1549, which landed in the Hudson River after both engines had stopped while considering the possibility of returning to the runway and the need to consider the ground conditions in the analysis for safety evaluation [20].

Because emergency flight planning is a function used in emergencies, it should be achieved in the shortest possible time. Miwa et al. [22] proposed a real-time flight trajectory generator applicable to emergency landing approaches. Donato et al. [23] and Ding et al. [24] proposed optimization methods for emergency landing trajectories for small UAVs considering ground conditions such as population data, topographic data, and onboard camera images. Adler et al. [25], Vana et al. [26], and Arno et al. [27] proposed a method for flight planning for emergency landings, considering the effects of terrain to ensure the height of the ground surface.

While there has been much research on path optimization for low-speed aircraft such as UAVs that consider the ground conditions (e.g., distributions of buildings and population), the research for high-speed aircraft has gone as far as considering the terrain. Therefore, research that considers ground conditions for high-speed aircraft is expected.

## 3. Flight path generation

### 3.1 Overview

Normally, we consider the flight path to be a line where the aircraft can fly from the departure position to the arrival position; however, an infinite number of flight paths can be generated to connect these points. Flight path generation involves finding an optimal path by considering one or more conditions, such as the performance of the aircraft, weather conditions, and economic performance. As shown in Figure 1, the shortest flight path (red line) is the Global Circle Route (GCR). However, when strong winds are blowing, the economic path (cyan line) differs from the shortest path. Furthermore, the safest path (orange line) ensures the aircraft can land at the nearest runway during an emergency.

For a given flight path, the economics and safety are estimated by calculating the fuel consumption and distance to the runways using the aircraft model. In this study, we focus on generating the optimal flight path by considering these conditions (e.g., economy and safety) simultaneously. The optimal flight path can be obtained by evaluating the cost function and solving the optimization problem.

### 3.2 Flight path and control parameters

In this research, we define the flight path $\boldsymbol{p}$ as a 4-dimensional state vector, including not only the down-range $x$, the cross-range $y$, and the altitude $z$, but also the calibrated airspeed $v_C$: $\boldsymbol{p} = [x, y, z, v_C]$.

To control the aircraft following the flight path, we define the flight control $\boldsymbol{c}$ as a 3-dimensional control vector including the thrust $T$, track angle $\phi$, and flight path angle $\theta$: $\boldsymbol{c} = [T, \phi, \theta]$.

## 3.3 Aircraft model

The conventional three-dimensional, six-degree-of-freedom aircraft motion model was approximated by a point mass motion model that omits the variables of aircraft attitude. And the transition of the state of the path $p$ between any two nodes was assumed to be linear and independent of the Nodes passed before or after the nodes to be able to apply the dynamic planning method.

To estimate the forces (lift, drag, and thrust) on the aircraft in flight, the aircraft parameter database BADA (base of aircraft data) [9], provided by Eurocontrol and widely used for aircraft trajectory simulation in air traffic modeling, was used. The atmospheric characteristics were assumed to follow the international standard atmosphere (ISA) model. Equations (1) and (2) represent the vertical force and energy balances, respectively:

$$L = \frac{1}{2}\rho(z)v_T^2 C_L S_{ref} = mg, \tag{1}$$

$$(T - D)v_T = mg\frac{dz}{dt} + mv_T\frac{dv_T}{dt}, \tag{2}$$

where $\frac{1}{2}\rho v_T^2$ is the dynamic pressure, which can be calculated from the atmospheric density $\rho(z)$ at altitude $z$, reference area for aircraft $S_{ref}$, and flight speed $v_T$.

$C_L$ is the lift coefficient for a given flight condition $p[x, y, z, v_T]$, which can be calculated using the airframe mass $m$.

$D$ is the drag force, which can be calculated from Eqs. (3) and (4) for a given $C_L$, calculated by Eq. (1):

$$C_D = C_{D0} + C_{D2}C_L^2, \tag{3}$$

$$D = \frac{1}{2}\rho(z)v_T^2 C_D S_{ref}, \tag{4}$$

where $C_{D0}$ and $C_{D2}$ are the zero-lift drag and drag-due-to-the-lift factor for the aircraft specified in the BADA model, respectively.

During the flight, the rate of increase of the potential and kinetic energy is equal to the work due to the thrust and aerodynamic forces acting on the aircraft, respectively. The necessary thrust force $T$ can be calculated based on the law of the conservation of energy.

Note that $v_T$ is the true airspeed, which is calculated from the calibrated airspeed $v_C$ and altitude $z$.

Wind changes the flight distance and affects fuel consumption; for example, a strong headwind increases the flight (air) distance and fuel consumption.

## 3.4 Cost Function

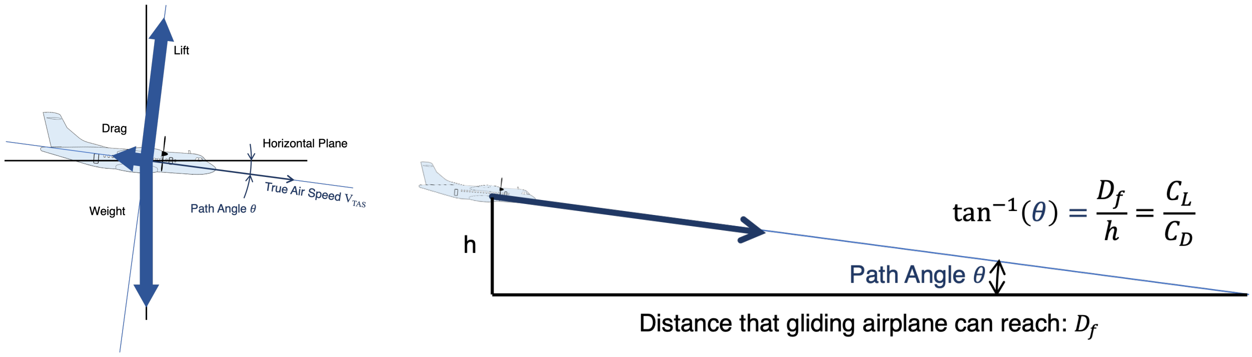
Using the aircraft model, for a given flight path $\boldsymbol{p}$, the following cost function is defined to evaluate the economic cost $C$ and flight safety risk $R$.

$$u = w_1 C(\boldsymbol{p}) + w_2 R(\boldsymbol{p}), \tag{5}$$

where $w_1$ and $w_2$ are the weight coefficients that define the importance of each factor ($w_1, w_2 \in [0,1]$), which can be selected based on flight conditions, such as flight mission and payload importance. $w_1 = 1.0$ and $w_2 = 0.0$ means that the aircraft is sufficiently safe and only economic factors need to be considered; $w_1 = 0.0$ and $w_2 = 1.0$ means that safety should be considered a priority. The optimal flight path is obtained by minimizing the evaluation value of Eq. (5).

$C(\boldsymbol{p})$ is the economics of the flight path $\boldsymbol{p}$. In this research, we only use fuel consumption to calculate the economic cost, which is a major factor in operating costs. For a jet aircraft, the fuel consumption can be calculated by integrating the fuel flow as a linear function $f$ of airspeed $v_T$ and thrust force $T$:

$$C(\boldsymbol{p}) = \int f(v_T, T)dt. \tag{6}$$




(a) Aircraft model (b) Gliding path slope

Figure 2 – Flyable distance.

Using the constant values $C_{f_1}$ and $C_{f_2}$ specified in the BADA model for the airplane model, we estimated the fuel flow as follows:

$$f(v_t, T) = C_{f_1} T (1 + \frac{v_T}{C_{f_2}}). \tag{7}$$

The minimum value of the fuel flow is limited to the value at idle.
$R(\boldsymbol{p})$ is the safety of flight path $\boldsymbol{p}$, which is defined as the integral of the risks of all positions on the flight path as follows:

$$R(\boldsymbol{p}) = \int r(D_r, D_f) dt, \tag{8}$$

where $D_r$ is the distance from the emergency location to the nearest runway and $D_f$ is the flyable distance (i.e., the distance that can be reached by gliding while all engines are inoperable), as shown in Fig. 2. $r$ is the risk function used to determine if the distance to the runway is sufficiently close for a successful emergency landing:

$$r(D_r, D_f) = \begin{cases} 0 & (kD_f \geq D_r), \\ (\frac{D_r - kD_f}{D_f - kD_f})^2 & (kD_f < D_r), \end{cases} \tag{9}$$

where $k$ is a coefficient that defines how close to the nearest runway is sufficiently safe. If the flyable distance is larger than $k$ times the distance to the nearest runway, the risk $r$ would be $0$, whereas if it is far from any runways, the flight would be considered high risk.

## 3.5 Constraints and Boundary Conditions

In the BADA, the following parameters of the aircraft performance constraints have been identified, which are used as the constraint conditions for searching for the optimal flight path using Eq. (5).

- Thrust: The maximum thrust in the climb and take-off phases $T_{maxclimb}$ is defined; this value varies with the pressure altitude $z_p$. The minimum thrust in the descent phase $T_{mindes}$ is defined as the following simple function:

$$T_{mindes} < T < T_{maxclimb}, \tag{10}$$

$$T_{maxclimb} = f(z_p), T_{mindes} = C_{Tdes} T_{maxclimb}, \tag{11}$$

  where $C_{Tdes}$ is the aircraft specific constant.

- Altitude: The upper limit of altitude $z_{max}$ is specified for each aircraft model, and its value varies with the temperature and mass of the aircraft.

$$z < z_{max} \tag{12}$$

- Speed: The upper and lower speed limit values $(v_{Tmin}, v_{Tmax})$ are specified for each aircraft model in terms of the calibrated airspeed (CAS).

$$v_{Cmin} < v_C < v_{Cmax} \tag{13}$$

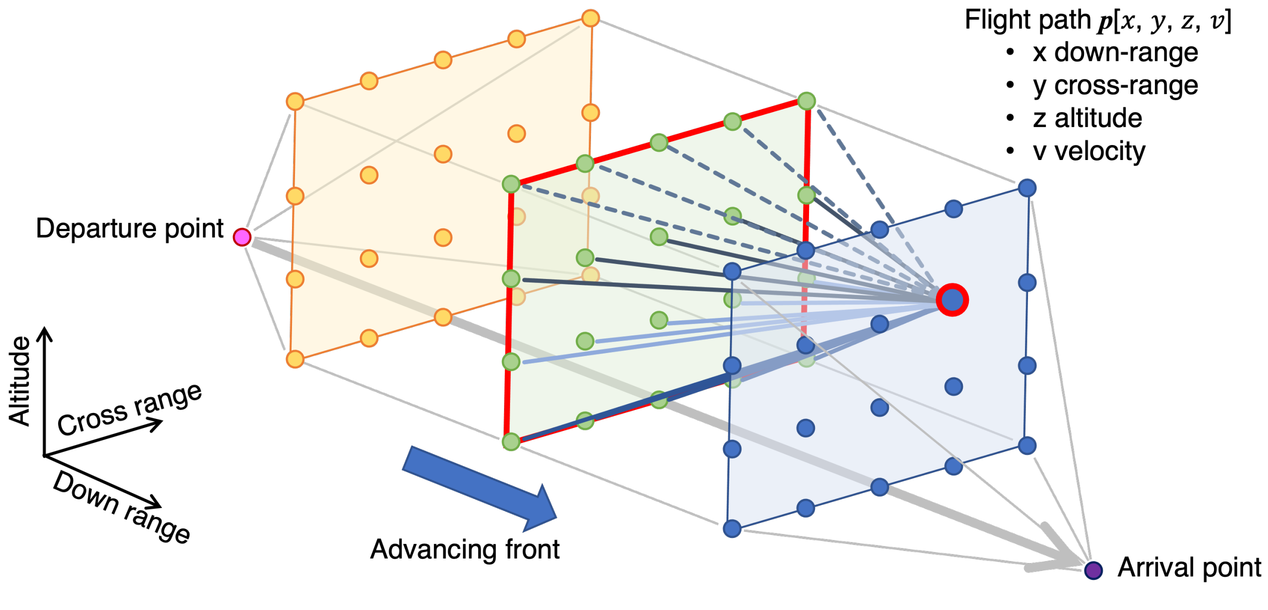



Figure 3 – Concept of graph structure for dynamic planning.

### 3.6 Optimization Method

Depending on the local conditions (e.g., the distribution of bad weather areas and airports affects the entire flight), many local optimal solutions may exist. To find the optimal flight path, we apply a dynamic planning method, Dijkstra's algorithm [10], to minimize the cost function of Eq. (5) by considering the aircraft model of Eq. (2) and the constraints conditions of Eqs. (10),(12), and (13).
Figure 3 illustrates the graph structure used for dynamic planning. The flight paths were separated into several short paths by setting multiple nodes. By calculating the cost through one node to each unvisited neighbor node and updating the costs of neighbor nodes if they are smaller, the optimal path with minimal cost can be obtained.

## 4. Experiment

### 4.1 Setup

*Aircraft model*

We created an aircraft model based on the data of a B777 using the parameters specified in the BADA. A Boeing777 is a typical passenger aircraft that is currently in use worldwide. The effectiveness of the created model was verified by comparing the calculated fuel consumption with the actual fuel consumption [19]. The lift-to-drag ratio under engine inoperation is approximately 15, which changes with the altitude and weight of the aircraft $C_L/C_D \approx 15$. Therefore, at an altitude of $h$, the glide distance $D_f$ (i.e., the flyable distance after an emergency) is approximately $D_f = 15h$.

*Analysis space*

Figure 4 illustrates the analysis space. The route from Tokyo International Airport (Haneda) to Okinawa Airport (Naha) was selected to confirm the effectiveness of the proposed flight path generation method. The red line represents the GCR as a reference, which is the shortest path. The red dots show the positions of landable runways [28] that have sufficient length (>2500 m) for landing large passenger aircraft. The closer a flight path is to the red line of the GCR, which is the shortest path on this route, the lower the fuel consumption. However, aircraft fly over the ocean, which increases the risk of not reaching a runway in an emergency; if a flight path is close to land, the aircraft would be safe to land on a runway in an emergency. In the latter case, the total flight distance will be longer, and fuel consumption will increase, which will lead to lower economic efficiency.
The area within the blue lines represents the search and analysis space in the experiment. We set a strong northwest wind on the route to simulate a strong jet stream near Japan, which is typical in winter. The wind speed reaches a maximum value of 100 m/s at an altitude of 10,000 m. Because

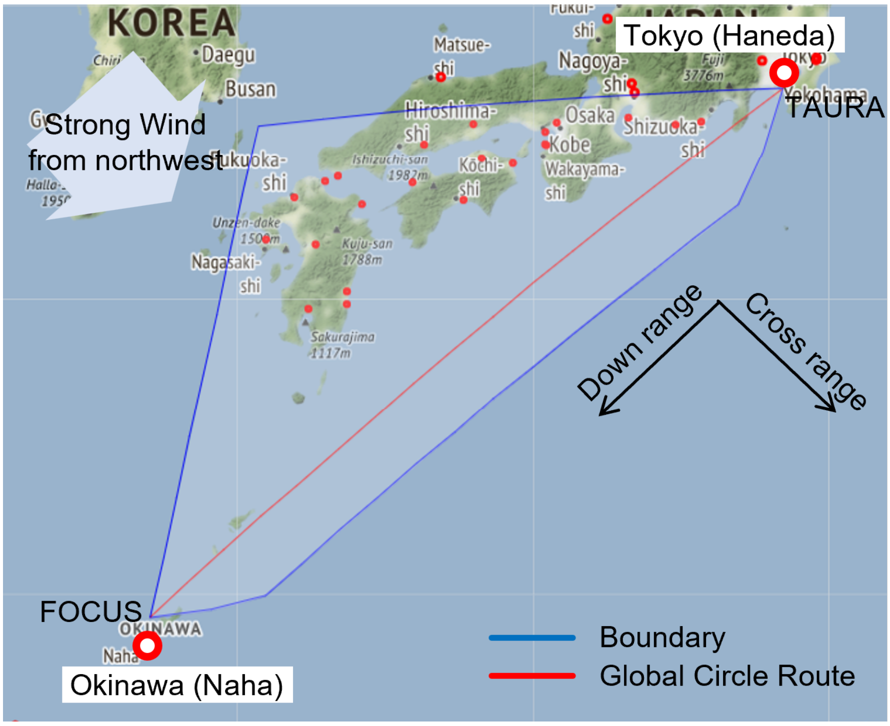



Figure 4 – Analysis space of the Haneda-Naha route.

Table 1 – Graph structure parameters

| | | |
|---|---|---|
| Down-range ($x$) | 0 - 1,492 km | From Taura to Focus |
| | $\Delta x \approx 93.3$ km | |
| Cross-range ($y$) | -610.5 - 115.5 km | |
| | $\Delta y \approx 16.5$ km | $\Delta\Psi \approx 10$ deg |
| Altitude ($z$) | 4,000 - 39,000 ft | |
| | $\Delta z \approx 2,500$ ft | $\Delta\Upsilon \approx 0.5$ deg |
| Airspeed ($v_C$) | 150 - 180 kt | |
| | $\Delta v_C \approx 10$ kt | |

the strong wind is from the northwest and there is no landable runway on the ocean side, we set a narrower search space on the south side of the GCR.
Table 1 lists the parameters of the graph structure (nodes and edges) used for the dynamic planning. The down-range between the waypoints of Taura (Haneda departure) and Focus (Naha arrival) is 1492 km, which is equatorially separated into 16 paths. The widest cross-range was approximately 726 km. When passing the waypoints of Taura and Focus, the altitude should be higher than 9,000 ft and 4,000 ft, respectively. Therefore the altitude ranged from 4,000 ft. to the maximum altitude of 39,000 ft. The graph consists of a total of 26,098 nodes.

## 4.2 Result

Figure 5 shows the top view of the flight paths obtained for different pairs of weight coefficients $(w_1, w_2)$ in Eq. (5). The red line shows the GCR (i.e., the shortest path). The purple line shows a sample actual flight path, which was flown last year; this is very close to the GCR for economic reasons. Based on the calculations of our method, the most economical flight path ($w_1 = 1.0$, $w_2 = 0.0$; cyan line) was over the ocean and close to the GCR. This path exhibited a slight shift to the north owing to the influence of the strong jet stream. During the early and late stages of flight, fuel consumption can be improved by flying upwind at low altitudes with low wind speeds. At a high altitude with a high wind speed, the fuel consumption would be better for flying with a tailwind. With an increase in the safety weight $w_2$, the flight paths gradually moved northward and closer to the land. The safest flight plan ($w_1 = 0.0001$, $w_2 = 0.9999$; white line) almost follows the coastline, which is close to the runways.

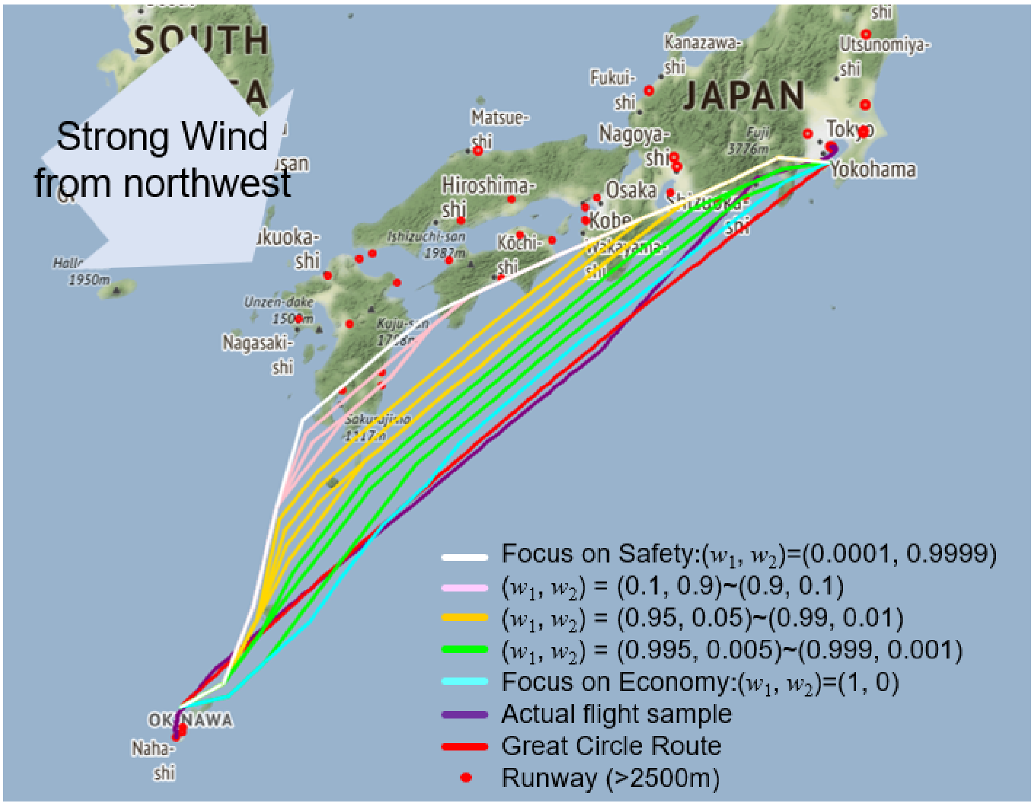



Figure 5 – Optimized Flight Paths (Longitude. vs. Latitude).

Note that the weight coefficient for the economy cannot be set to zero because the risk function of Eq. (9) is modeled to be insensitive when sufficiently close to the runway.

Figure 6 shows the changes in altitude over time. The flight levels were similar for all cases. The difference in flight time between the most economical case (cyan line) and the safest case (white line) was only approximately 300 s.

Table 2 shows the details of the typical paths obtained for different pairs of weight coefficients $(w_1, w_2)$. As $w_1$ increased, the flight time, flight distance, and fuel consumption improved. However, as $w_2$ increased, the flight path became further away from the shortest path, and the flight distance and ground distance increased. However, the flight safety risk (i.e., the distance to runways) decreased.

Figure 7 shows the relationship between operating cost (fuel consumption) and flight safety risk for different weight coefficients $w_1$ and $w_2$. From this relationship, the desired optimal flight path can be determined according to conditions such as flight mission and payload importance.

## 5. Conclusion

In this study, we proposed a method to automatically generate the flight path in various flight situations by simultaneously considering the flight economy (e.g., fuel consumption) and safety (e.g., emergency landing). We formulated and solved a multiparameter optimization problem. An aircraft model was created to calculate the dynamic characteristics using the base of aircraft data (BADA). Using this model, we were able to estimate the fuel consumption from flight conditions (flight path, airspeed, etc.) and weather conditions (wind speed), which were used to evaluate the economics of the flight. Additionally, we were able to estimate the flyable distance in a loss-of-thrust emergency, which was used to calculate the risk by comparing it with the distance to the nearest airport. Dijkstra's algorithm, a dynamic planning method, was used to find the optimal flight path by minimizing fuel consumption and flight risk. The experimental results show that the proposed method can generate different flight paths by setting different values for the weight coefficients. In the most economical case, the obtained flight path was over the ocean and close to the GCR. With an increase in the safety weight coefficient, the flight path gradually moved closer to land. In the safest case, the flight path almost followed the coastline. Using this relationship between economy and safety, the optimal

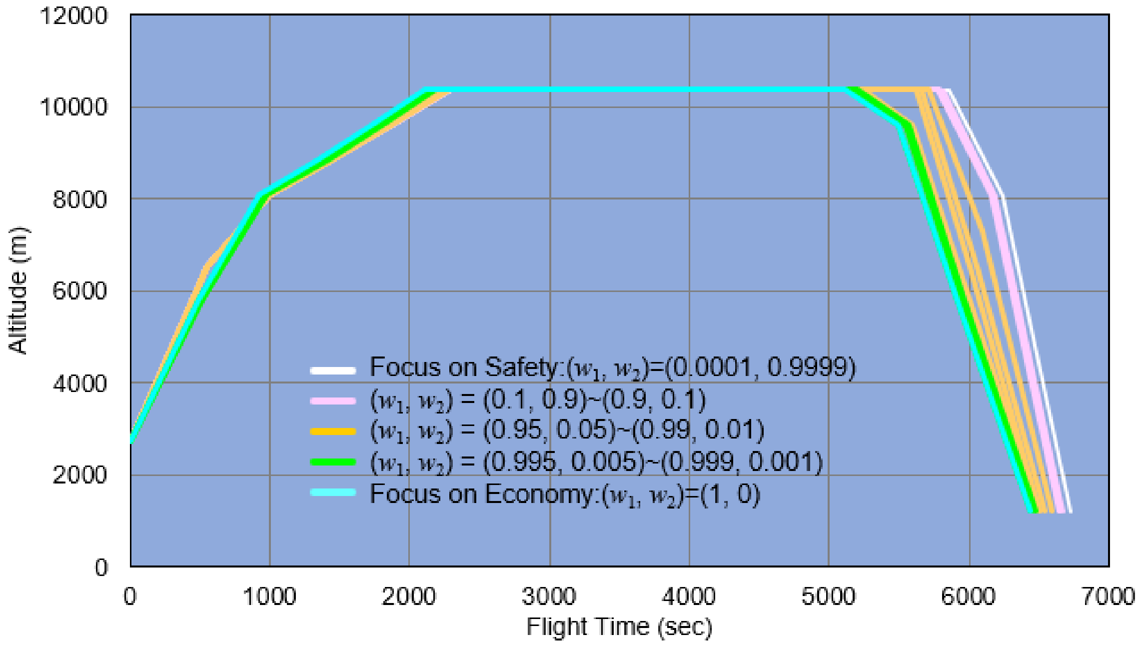



Figure 6 – Optimized Flight Paths (Flight time - Altitude).

Table 2 – Detailed result of obtained flight path with different weight coefficient

| Weight coefficient | | Flight Time | Flight Dist. | Ground Dist. | Fuel Burn | Risk |
|---|---|---|---|---|---|---|
| $w_1$ | $w_2$ | (s) | (km) | (km) | | |
| 0.0001 | 0.9999 | 6727 | 1666 | 1583 | 0.1210 | 0.443 |
| 0.8 | 0.2 | 6655 | 1647 | 1568 | 0.1197 | 0.443 |
| 0.9 | 0.1 | 6642 | 1644 | 1565 | 0.1195 | 0.445 |
| 0.95 | 0.05 | 6587 | 1625 | 1551 | 0.1173 | 0.480 |
| 0.98 | 0.02 | 6548 | 1610 | 1540 | 0.1154 | 0.532 |
| 0.99 | 0.01 | 6508 | 1592 | 1524 | 0.1134 | 0.691 |
| 0.995 | 0.005 | 6476 | 1582 | 1513 | 0.1128 | 0.767 |
| 0.997 | 0.003 | 6453 | 1577 | 1507 | 0.1124 | 0.867 |
| 0.999 | 0.001 | 6443 | 1574 | 1508 | 0.1120 | 1.111 |
| 1.0 | 0.0 | 6439 | 1573 | 1505 | 0.1119 | 1.331 |

flight path can be determined according to these conditions.

In future work, we aim to establish a flight path optimization method for emergency landing by considering the aircraft dynamic model and the ground conditions (e.g., the distribution of multiple buildings, population, and topography). Actual weather data also be considered to calculate economics and safety.

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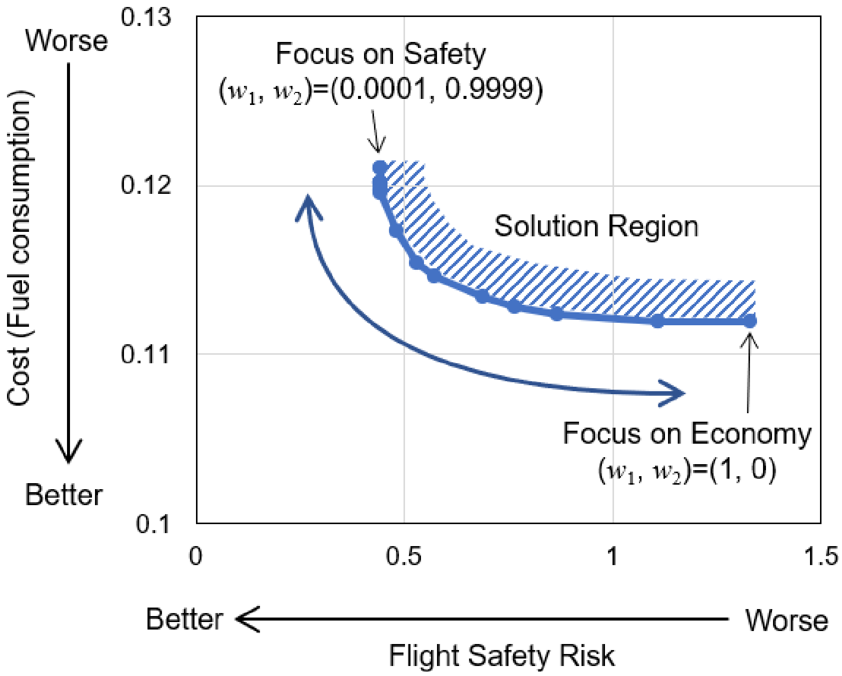


Figure 7 – Impacts of the coefficients $(w_1, w_2)$ on economy and safety.

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