2021年度共同利用研究報告書

2022年03月23日

所属・職名 German Aerospace Center (DLR) Institute of Atmospheric Physics・Postdoctoral researcher

Hiroshi Yamashita

		整理番号	20210018	
1.研究計画題目	環境負荷を考慮した航空経路の多目的最適化			
2.新規・継続	新規			
3.種別	一般研究			
4.種目	短期共同研究			
5.研究代表者	氏名	Hiroshi Yamashita		
	所属部局名	German Aerospace Center (DLR) Institute of Atmospheric Physics	職名	Postdoctoral researcher
6.研究実施期間	2021年12月15日(水曜日)～2021年12月16日(木曜日)			
7.キーワード	多目的最適化，微分トポロジー，構造安定性，トポロジー解析可視化			
8.参加者人数	13人			

9.本研究で得られた成果の概要

Climate impact due to aviation emissions is a topic studied world-wide because of its importance for a sustainable society, and now aviation industry is required to reduce the impact. In recent years, a climate-optimized routing has been proposed as an important operational measure for reducing the climate impact from aviation. Benefits of the climate-optimized routing have been examined before. On the other hand, many studies showed that there is a trade-off between climate impact and economic cost. Technically, multi-objective flight trajectory optimizations can be solved and pareto-optimal solutions can be found by model simulations; however, a following decision-making process takes time, because a dimensionality of pareto fronts becomes high in such real-world optimization problems.

The aim of this study is to develop an efficient method to explore a geometry of pareto fronts among multiple objectives, understand it, and select the most preferable solution from the pareto-optimal solutions promptly. The three-objective flight trajectory optimizations were solved with respect to flight time, fuel use and climate impact under realistic weather conditions by using the chemistry–climate model EMAC. We applied the knee point analysis method based on the Reed graph to the obtained non-dominated solutions. For two exemplary cases, we successfully captured some knee points for the non-dominated solutions and analyzed the geometry of the pareto fronts. Further analyses are carried out, which could find new eco-efficient flight routes that human experts do not notice.

This research deals with the real-world and concrete optimization problem on aviation and climate change on the basis of numerical simulations. However, the problem has the essential core of the issue; that is, the analysis of high-dimensional fields. To exchange some ideas among researchers who work on multi-objective optimizations, differential topology and meteorology, the IMI Short-term Joint Research workshop, “Multi-objective optimization of flight trajectories for mitigating the climate impact from aviation” was held online on December 15–16, 2021. The fruitful discussion and knowledge exchanges are helpful in developing an efficient decision-making method.

FY2021 IMI Joint Usage Research Program Short-term Joint Research

Multi-objective optimization of flight trajectories for mitigating the climate impact from aviation

1. Introduction

Climate impact of aviation emissions is a topic studied world-wide because of its importance for a sustainable society, and thus aviation industry is required to reduce the impact. The aviation climate impact consists of carbon dioxide (CO_2) emissions and of non-CO_2 effects, which consist of concentration changes of ozone, methane, water vapor, persistent linear contrails and contrail-induced cirrus clouds. They have different timescales of the climate impact. Therefore, the impact of both CO_2 and non-CO_2 effects must be considered to evaluate the aviation climate impact.

The current aircraft routing strategy in the airline industry tends to optimize the financial cost of operation with little consideration on the environmental sustainability. However, if additional costs (e.g., environmental taxes) for aviation climate impact of the CO_2 and non-CO_2 effects are included in the operating cost, another aircraft routing strategy is needed; that is, both the operating cost and the climate impact of aviation emissions need to be considered for the sustainable development of aviation. Generally, a trade-off exists between the operating cost and the climate impact [1].

To support airlines in finding a practical solution to the trade-off, eco-efficient flight trajectories need to be found promptly. A multi-objective optimization of flight trajectories can be solved and a set of pareto-optimal solutions can be found in model simulations; however, the following decision-making process can take time, because the dimensionality of pareto fronts becomes high in such real-world optimization problems. An efficient method needs to be developed to explore a geometry of the pareto fronts among multiple objectives, understand it, and select a compromise solution (i.e., an eco-efficient solution) from the pareto-optimal solutions according to user preferences.

The aim of this study is to develop an analysis method that enhances the understanding of the trade-offs among multiple routing strategies and selects the most preferable optimal solution promptly. The three-objective flight trajectory optimizations were solved with respect to flight time, fuel use and climate impact under realistic weather conditions by using the chemistry–climate model EMAC [2,3]. We attempted to use the Reeb graph to explore topological structures of the obtained pareto fronts [4].

2. Methods

2.1 The chemistry–climate model EMAC

The EMAC model is a numerical chemistry and climate simulation system that includes submodels describing tropospheric and middle atmosphere processes and their interaction with oceans, land, and influences coming from anthropogenic emissions [2,3]. It uses the second version of the Modular Earth Submodel System (MESSy2) to link multi-institutional computer codes. The core atmospheric model is the fifth generation European Center HAMburg general circulation model (ECHAM5 [5]). For the present study, we applied EMAC (ECHAM5 version 5.3.02 and MESSy version 2.53) in the T42L90MA-resolution, i.e., with a spherical truncation of T42 (corresponding to a quadratic Gaussian grid of approx. 2.8 by 2.8 degrees in latitude and longitude) with 90 vertical hybrid pressure levels up to 0.01 hPa. The model setup comprised the E5 setup; the submodels AirTraf (version 2.0 [6]), CONTRAIL (version 1.0 [7]) and ACCF (version 1.0 [8]) were additionally employed. A one-year AirTraf simulation was carried out, where the round-trip flights between Frankfurt and New York were optimized with respect to the three aircraft routing strategies: flight time, fuel use and climate impact. Table 1 lists the simulation setups; other setups for the optimization parameters are described in Yamashita et al., 2020 [6].

Table 1 Setup for the AirTraf simulation

Parameter	Description
Simulation period	December 1, 2017– November 30, 2018
Flight plan	09:20 UTC FRA to JFK/21:40 UTC JFK to FRA
Aircraft/engine type	A330-301/CF6-80E1A2, 2GE051
Flight altitude	34,000 ft
Mach number	0.82

2.2 The Reeb–graph and Mapper

The Reeb graph enables one to detect knee points with a visualization of the geometry of the pareto fronts [9]. We examine how the Reeb graph captures the knee points and the geometry of the pareto fronts. We employed the method for approximating the analytic information with a nondominated front by using Mapper, which is an algorithm proposed by Singh et al., [10] in a topological data analysis. The hyper parameters of Mapper were set as follows: intervals = 100, overlap = 50, bins =10, and filter = $f_1 + f_2 + f_3$, where f_1: flight time, f_2: fuel use and f_3: climate impact (normalized to mean = 0 and stdev = 1).

3. Results

3.1 Optimized flight trajectories and non-dominated solutions

Figure 1 shows the results for two exemplary days in summer and in winter. We found 813 and 145 non-dominated solutions in summer and in winter, respectively; and trade-offs certainly exist between the three aircraft routing strategies for both seasons. Figure 1 (left) shows the flight trajectories corresponding to the three extreme optimal solutions of the minimum flight time, the minimum fuel use and the minimum climate impact; and to the other non-dominated solutions (trajectories in black). The minimum climate impact trajectory goes on the southerly route over the north-Atlantic. As shown in Table 2, with the small deviation of route, even 56.1

% of the climate impact can be reduced with increasing flight time and fuel use, compared to those of the minimum flight time trajectory.

In Fig. 1 (right), we similarly compare the flight trajectories for the three extreme optimal solutions with the other non-dominated solutions in winter. This synoptic situation corresponds to the East Atlantic pattern, which consists of a north-south dipole of anomaly centers, spanning the north-Atlantic from east to west. The strong central jet stream appears under the synoptic situation, as shown in green contour lines. Therefore, those extreme optimal trajectories go on the northerly route to avoid the strong jet stream. The minimum fuel and the minimum climate impact trajectories are very similar; nevertheless, the latter achieves 2.2 % reduction in the climate impact (Table 3).

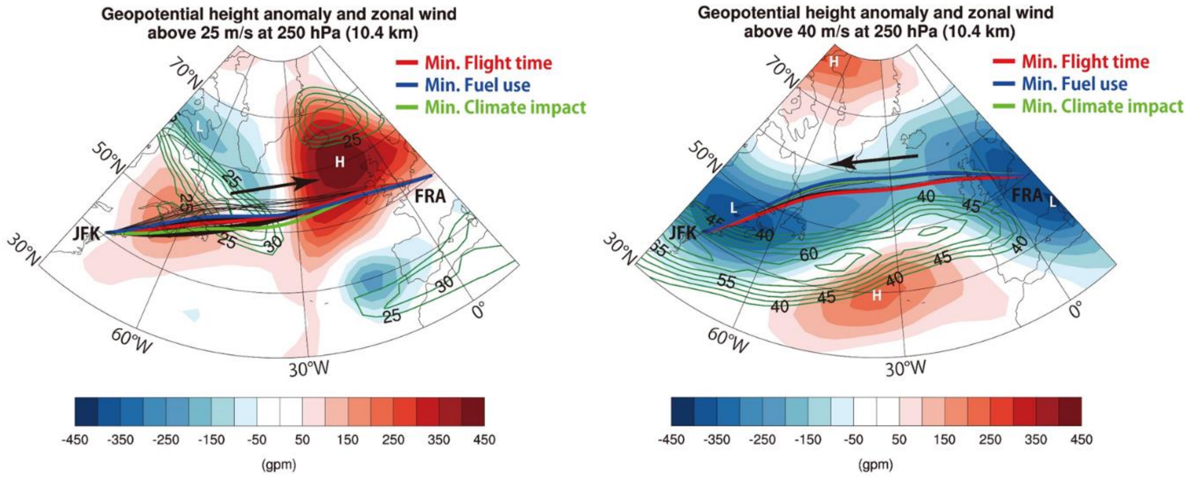

Figure 1 The optimized flight trajectories (left) on June 28, 2018, eastbound flight; and (right) on December 28, 2017, westbound flight.

Table 2 Three extreme optimal solutions on June 28, 2018 with their objective function values

Solution	Flight time, h	Fuel use, t	Climate impact, E–9 K
Min. flight time	6.69	39.5	4.1
Min. fuel use	6.71	39.2	5.2
Min. climate impact	6.72	40.0	1.8

Table 3 Three extreme optimal solutions on Dec. 28, 2017 with their objective function values

Solution	Flight time, h	Fuel use, t	Climate impact, E–9 K
Min. flight time	7.40	39.39	1.358
Min. fuel use	7.43	39.20	1.334
Min. climate impact	7.42	39.29	1.328

3.2 Pareto front analyses by Mapper

The non-dominated solutions change every flight because of daily-changing synoptic situations. To analyze a structure of the trade-offs between different aircraft routing strategies and to understand the trade-offs promptly, we applied the knee point analysis method with Mapper [4] to our yearly data set of the non-dominated solutions. Figure 2 shows the scatter plot and the parallel coordinate plot of the non-dominated solutions, in which some critical points are marked by the Mapper graph. In total, 28 and 55 knee points were found on June 28, 2018 and on December 28, 2017, respectively. For the next step, the flight trajectories that correspond to those knee points should be observed in detail, and their physical meaning needs to be examined further. An application of the Reeb space algorithm [10] that works for arbitrary dimensional domains to our optimization problem will be also studied.

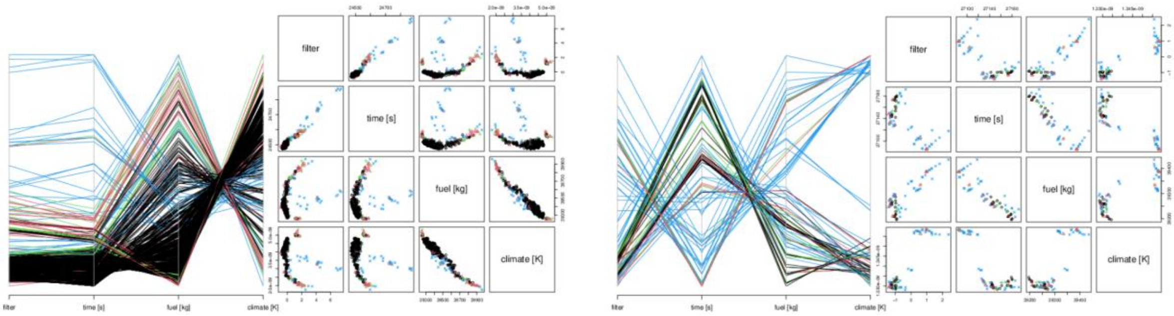

Figure 2 The parallel coordinate plot and non-dominated front (left) on June 28, 2018 and (right) on December 28, 2017; (red) minima, (green) maxima and (blue) isolated points.

4. Summary

We employed the chemistry–climate model EMAC coupled with the air traffic simulation model AirTraf to perform the three-objective flight trajectory optimizations under daily changing weather conditions from December 1, 2017 to November 30, 2018. The round-trip flights between Frankfurt and New York of an Airbus A330 aircraft were optimized successfully, and the yearly data set of non-dominated solutions were obtained. We found that the non-dominated solutions significantly change every flight because of daily-changing synoptic situations. We applied the knee point analysis method with Mapper to the yearly data set of non-dominated solutions in order to explore topological structures of the obtained pareto fronts. The results showed 28 and 55 knee points on June 28, 2018 and on December 28, 2017, respectively. The obtained flight trajectories corresponding to those knee points need to be further analyzed, and their physical meaning should be examined. With that, we would develop a method to understand the trade-off structure easily and to select the most preferable optimal solution promptly.

As for the research collaboration activities, the IMI Short-term Joint Research workshop, “Multi-objective optimization of flight trajectories for mitigating the climate impact from aviation” took place online on December 15–16, 2021. The aim of this workshop was to exchange some ideas among researchers who work on multi-objective optimizations, differential topology and meteorology. The fruitful discussion and knowledge exchanges are helpful in developing an efficient decision-making method further. To prepare the workshop, we had research progress meetings three times on August 20, 2021, October 18, 2021 and November 4, 2021, where we discussed simulation results and addressed data management. The outcome that we obtained from the one-year research collaboration will be submitted to an international journal.

Acknowledgements

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九州大学 IMI 共同利用・短期共同研究

Multi-objective Optimization of Flight Trajectories for Mitigating the Climate Impact from Aviation

環境負荷を考慮した航空経路の多目的最適化

日時：　2021年12月15日（水）15:30 ~ 17:00 (JST)
場所：　Zoomによるオンライン開催
研究代表者：　山下 博　（Postdoctoral researcher, German Aerospace Center [DLR] Institute of Atmospheric Physics）

※プログラムは都合により変更になる場合がありますので予めご了承ください。
最新情報はホームページをご覧ください。

12月15日（水）

15:30-15:35
Opening remarks

15:35-15:55
Multi-objective Flight Trajectory Optimization by Using EMAC/AirTraf
Hiroshi Yamashita and Bastian Kern (German Aerospace Center)

15:55-16:15
Post-optimal Analysis and Decision Making Assistance Using Mapper
Naoki Hamada (KLab Inc.)

16:15-16:35
A Quest for Explicitly Multi-Modal Benchmarks for Multi-Objective Optimization
Daisuke Sakurai (Kyushu University)

16:35-16:55
Thinking Multi-objective Optimization Problems Topologically
Likun Liu (Kyushu University)

16:55-17:00
Closing remarks

※研究実施期間：2021 年 12 月 15 日（水）～ 12 月 16 日（木）
※公開日：2021 年 12 月 15 日（水）