

REDUCING AIR TRAFFIC COMPLEXITY IN JAPANESE AIRSPACE THROUGH MINOR LATERAL TRAJECTORY ADJUSTMENTS

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Abstract

We present a trajectory optimization method that reduces air traffic complexity through minor lateral adjustments of existing trajectories while preserving the operational integrity of the traffic scenario. Existing trajectories are locally adjusted within a limited lateral deviation radius. The adjustment is formulated as a geometric optimization problem and solved using Grey Wolf Optimization. The trajectory optimization approach is applied to real surveillance data from Japanese airspace, analyzing the Tokyo feeding sector T25 in the Fukuoka FIR across three operationally relevant time windows. The method reduces the mean sector complexity by 14 to 26% and the peak complexity by up to 23%, while improving aircraft horizontal proximity.

Keywords: air traffic complexity, trajectory optimization, grey wolf optimization

1. Introduction

Trajectory optimization is a broad and active field of research. A wide range of approaches seeks to compute optimal trajectories with respect to objectives such as fuel burn, flight time, or contrail formation, either through classical optimization methods or, more recently, through Artificial Intelligence (AI)-based techniques [1, 2]. Many of these approaches pursue a theoretically optimal trajectory with respect to one or several performance criteria.

This pursuit, however, tends to abstract away operational constraints that govern Air Traffic Control (ATC). Separation requirements, approach procedures, handover points and times, all shape what can actually be flown. A theoretically superior trajectory, for instance in fuel burn or contrail impact, provides limited operational benefit if it cannot be integrated into the existing control environment. Consequently, optimization gains that disregard these constraints frequently fail to materialize in practice. What is required, therefore, is an optimization approach that preserves the operational integrity of the traffic scenario.

Building on this requirement, previous work introduced a trajectory adjustment method that reduces air traffic complexity through minor lateral modifications of existing trajectories [3]. Because segment lengths are preserved, the operational framework, including leg times, speed profiles, and handover conditions, remains intact, and no recalculation of flight performance is required. By abstracting the adjustment to a geometric problem, the method is computationally inexpensive and suitable for pre-tactical or tactical applications. However, this approach has been evaluated only on simulated traffic and within dynamic airspace concepts.

The present study extends this approach in two directions. First, the method is applied to real surveillance data in Japanese airspace. Second, it is evaluated within a conventional, statically sectorized airspace. The objective is to investigate whether minor lateral trajectory adjustments can reduce the traffic-induced complexity of sector T25, whose capacity is closely related to Air Traffic Controller (ATCO) workload [4, 5]. Air traffic complexity serves as an indirect indicator of this traffic-induced workload and can be computed from observable traffic data [6]. In previous work, the complexity factors dispersed across the literature were consolidated into a single computable metric [7].

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1.1 Structure of the document

This paper is organized as follows. Section 2. reviews the state of research on air traffic complexity and trajectory optimization. Section 3. introduces the traffic dataset utilized in this study and the browser-based visualization environment developed for the interactive comparison of original and optimized trajectories. Section 4. presents the methodology, comprising the trajectory adjustment method, the complexity-based objective function, and the optimization algorithm. Section 5. applies the approach to sector T25 and reports the obtained complexity reductions, followed by a discussion of the results. Section 6. concludes the document and outlines directions for future work.

2. State of research

Air traffic complexity is defined as the difficulty of controlling a given traffic situation and is regarded as a primary driver of controller workload and, consequently, of the sector capacity that this workload ultimately limits [4]. Observable traffic characteristics is linked to the cognitive effort of the ATCO, who must perceive, comprehend, and project the evolving situation [6, 8]. Complexity therefore does not measure controller workload directly. It represents the traffic-induced component of controller demand, whereas the workload experienced individually depends additionally on factors such as controller experience, equipment quality, and cognitive strategy [5]. Consequently, the mapping from complexity to perceived workload remains non-linear, context-dependent, and empirically non-uniform [5, 7]. While numerous metrics have been proposed, ranging from dynamic density to graph- and learning-based measures, they frequently relate to a specific experimental setup and are inconsistently applied, so that no generally accepted standard has emerged [9, 10]. Accordingly, prior work consolidated the dispersed complexity factors into a set of metrics, providing a computable complexity measure derived from observable traffic data, which is utilized in the present study [7].

Trajectory optimization has been studied often with efficiency-oriented objectives. Many approaches optimize four-dimensional trajectories for reduced fuel burn, flight time, or climate impact, employing simulation-based toolchains or dedicated performance models [11, 12]. The underlying problems are commonly reduced to vertical or longitudinal models [13] and solved by transcription into non-linear programs [14] or by pathfinding methods that account for local airspace restrictions [15]. By contrast, comparatively few studies treat air traffic complexity as the optimization target. Early work demonstrated that smoothing trajectories in multi-sector planning can reduce complexity by up to 50% [16]. Structural analyses further indicate that organizing aircraft into predictable flows can lower the cognitive complexity perceived by the controller [17]. While these findings confirm that trajectory structure influences complexity, optimization across multiple interacting aircraft has received limited attention. We previously introduced a lateral trajectory adjustment method that reduces air traffic complexity using Grey Wolf Optimization (GWO), while preserving segment lengths and thus flight time, speed profile, and operational conditions [3].

3. Framework

Collaborative Actions for Renovation of Air Traffic Systems (CARATS) Open Data from 2019, an anonymized surveillance dataset provided by the Japan Civil Aviation Bureau is used as the data source in this study. The data are stored in a local database and prepared for fast replay and systematic evaluation of air traffic scenarios.

For this purpose, a browser-based visualization tool is developed, Fig. 1. It loads Japanese sector geometries from GeoJSON data and trajectory data from the CARATS dataset. The map interface allows users to compare original trajectories with optimized trajectories, while also displaying the airspace structure. The visualization supports interactive filtering by time window, altitude range, target sector, and flight callsign prefix. In addition, the tool can draw configurable radius areas around waypoints, to visualize the spatial solution room for the optimizer. By clicking on a trajectory, users can highlight the corresponding pair of original and optimized routes and inspect detailed information such as aircraft type, origin and destination, altitude range, time spent inside the target sector, and spatial differences between the two routes.

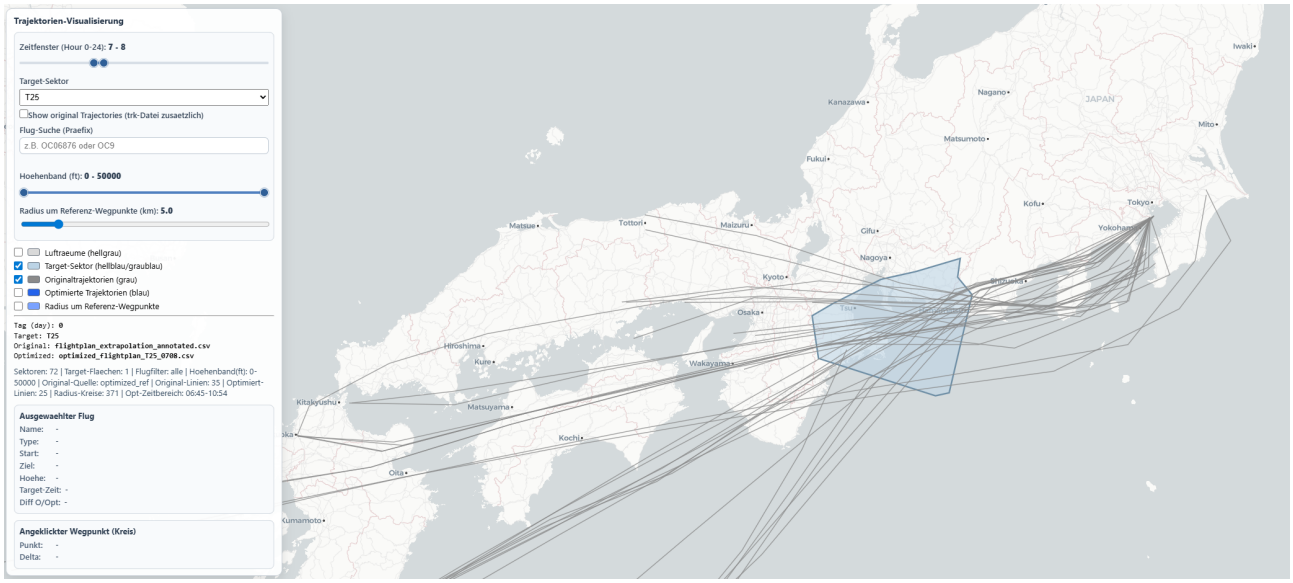


Figure 1 – Browser-based trajectory visualization environment used in this study. The control panel (left) allows filtering by time window, target sector, flight, altitude band, and the waypoint deviation radius, and toggling of individual map layers. The map (right) shows the target sector T25 (highlighted in blue) within the Fukuoka FIR and the original traffic trajectories (grey) for the selected time window.

4. Methodology: Trajectory Optimization

The trajectory adjustment method follows the approach introduced in [3] and is adapted to Japanese CARATS traffic data and the T25 application scenario. The method locally adjusts existing trajectories to reduce air traffic complexity while preserving the overall traffic structure and operational conditions. Each trajectory is first resampled into virtual waypoints at a fixed time interval Δt, yielding an ordered waypoint sequence. Each waypoint may be shifted laterally within a deviation circle of radius $r = 5$ km around its original position. At the same time, the length of each segment is preserved, maintaining the temporal structure of the trajectory and avoiding significant changes in flight time, speed profile, or fuel consumption. Because segment lengths and thus per-leg travel times are preserved, the timing structure represented by the original track data is kept, ensuring operational compatibility. To suppress oscillating (zigzag) flight paths, the acceptable deviation interval of each waypoint is restricted relative to the deviation chosen for the preceding waypoint, following the rule introduced in [3]. Anchor points, like the destination remain fixed.

The trajectory adjustment is parameterized by angular deviations relative to the original track direction. The maximum acceptable deviation angle θ_k for a segment of length d_k follows from the cosine rule (1), requiring the displaced waypoint to lie within the radius r while preserving d_k, see Fig. 2.

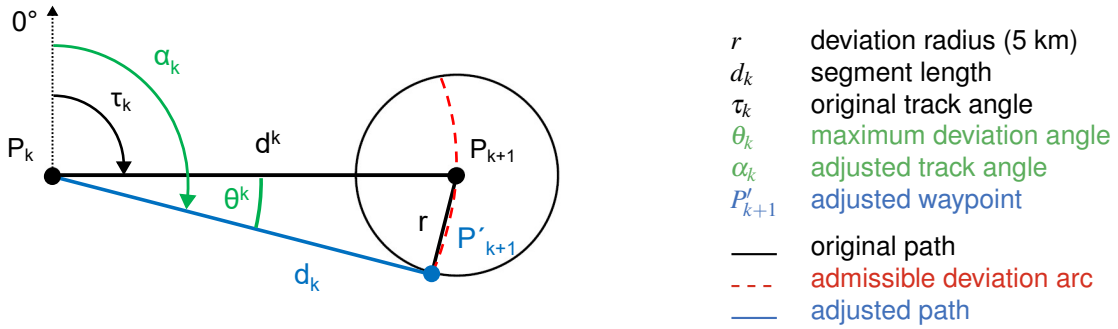


Figure 2 – Trajectory adjustment geometry with deviation radius, maximum deviation angle, deviation arc, deviated path, and deviated point [3].

$$\theta_k = \arccos\left(1 - \frac{r^2}{2\,d_k^2}\right) \tag{1}$$

For a segment with original track angle τ_k, the adjusted heading is then given by (2),

$$\alpha_k = \tau_k + u_k\,\theta_k, \tag{2}$$

where $u_k \in [-1,1]$ is the optimization variable. The adjusted waypoint position is computed recursively from the fixed anchor while preserving the original segment length.

4.1 Objective function: air traffic complexity metrics

The trajectory adjustment is driven by an objective function that quantifies air traffic complexity. Traffic complexity is a traffic-induced quantity derived from observable traffic data and serves as an indirect indicator of controller demand [5]. To capture it, the objective function combines three previously consolidated complexity metrics [7], M_1, M_2, and M_3, into a single time-dependent measure $C(t)$, see (3).

$$C(t) = \mathrm{M}_{1,t} + \mathrm{M}_{2,t} + \mathrm{M}_{3,t} \tag{3}$$

The three metrics combine 25 complexity factors, listed in Table 1, comprising 17 aircraft-related, six conflict-related, and two airspace-related factors.

Table 1 – Air traffic complexity factors examined in this study, including 17 aircraft-related, six conflict-related, and two airspace-related factors (cf. [7]).

category	component	factor
aircraft	count	Aircraft count (*ACT*)
		Share of maximum number of aircraft within the airspace (*C1*)
	density	Aircraft Density (*DNS*)
	altitude	Climbing or descending aircraft (*COD*)
		Altitude change (*AC*)
		Share of climbing aircraft (*C2*)
		Share of cruising aircraft (*C3*)
		Share of descending aircraft (*C4*)
	direction	Track variation (*VDF**)
		Heading change (*HC*)
	speed	Variance of speed (*C14*)
		Contrast ratio of speed (*C15*)
	distance	Closest point of approach (*CPA*)
		Minimum distance within 0-5 NM (*MD5*)
		Minimum distance within 5-10 NM (*MD10*)
		Minimum horizontal separation distance (*C9*)
		Minimum vertical separation distance (*C10*)
conflict	difficulty	Convergence angle (*ANG*)
		Conflict resolution difficulty (*C16*)
	distance	Conflict predicted within 25-40 NM (*CP40*)
		Conflict predicted within 40-70 NM (*CP70*)
	region	Aircraft neighboring conflict (*NBR*)
	time	Average time to conflict (*C12*)
airspace	boundary	Conflict near sector boundary (*PRC*)
		Traffic flow alignment with sector shape (*STR*)

Each metric aggregates its factors as a weighted sum, given in (4). Evaluating the individual factors requires several sub-calculations involving non-linear functions, for example, the prediction of closest points of approach or convergence angles between aircraft pairs.

$$\begin{aligned}
\mathrm{M}_{1t} &= 0.02\,\mathrm{ACT}_t + 0.33\,\mathrm{DNS}_t + 0.05\,\mathrm{CPA}_t + 0.11\,\mathrm{ANG}_t \\
&\quad + 0.04\,\mathrm{NBR}_t + 0.08\,\mathrm{PRC}_t + 0.11\,\mathrm{COD}_t + 1.0\,\mathrm{VDF}_t^* \\
&\quad + 0.07\,\mathrm{STR}_t \\
\mathrm{M}_{2t} &= 2.17\,\mathrm{HC}_t + 0.88\,\mathrm{AC}_t + 1.02\,\mathrm{MD5}_t + 1.18\,\mathrm{MD10}_t \\
&\quad + 1.85\,\mathrm{CP40}_t + 1.85\,\mathrm{CP70}_t \\
\mathrm{M}_{3t} &= \mathrm{C1}_t + \mathrm{C2}_t + \mathrm{C3}_t + \mathrm{C4}_t + \mathrm{C9}_t + \mathrm{C10}_t + \mathrm{C12}_t \\
&\quad + \mathrm{C14}_t + \mathrm{C15}_t + \mathrm{C16}_t
\end{aligned} \tag{4}$$

The optimization objective is to minimize the time-integrated complexity over the investigated time horizon, see (5),

$$\min \sum_{t \in T} C(t), \tag{5}$$

where T denotes the set of evaluated time steps.

4.2 Optimization metaheuristic: grey wolf optimization

Minimizing the objective in (5) over the adjustable track angles of all aircraft is a non-linear optimization problem whose search-space dimension increases with the number of adjustable waypoints per trajectory and the number of simultaneous flights in the sector [3]. An exhaustive deterministic search is impractical, and a population-based metaheuristic optimization algorithm, GWO [18], is used instead. At each iteration, a population of candidate solutions explores the search space, guided by the best solutions found so far. The algorithm parameters were adopted from the tuning reported in [3], namely a maximum of 1300 iterations and a population of 400 wolves, with the control parameter a decreasing linearly from 2.5 to 0.

5. Application

Sector T25 within the Fukuoka Flight Information Region (FIR) is selected as the application case because it plays an important role for arrivals to RJTT and contains interacting arrival and departure flows. Fig. 3 shows radar tracks and the sector configuration for nominal northerly-wind operations on an example day in December 2019 [19]. Among the air traffic flows arriving at RJTT from the southwest, traffic passing through the T25 sector is the most congested, resulting in a high frequency of radar vectoring by ATCOs. Therefore, this study focuses on the complexity analysis of the T25 sector. The RJTT arrival sequencing task starts at the entry into T25, approximately 200 NM before touchdown. If sequencing is not fully realized upon exit from T25, the residual task is transferred to downstream control sectors before the flow enters Tokyo ACA. The flow is required to maintain 10 NM longitudinal spacing on entering Tokyo ACA, at 70-80 NM to touchdown. Sector T25 poses an operationally challenging airspace, with the following major traffic delivery objectives: deliver a major arrival flow in vertical movement, create and maintain 10 NM longitudinal spacing for the arrivals, and deliver major departure flows, which are also in vertical movement and in conflict with the arrival flow. T25 is the most studied area control sector within the Fukuoka FIR (e.g. Human-in-the-Loop (HITL) simulation experiment (CITES)). It also serves departures and arrivals of the airports in the area.

An application of complexity metrics to T25 is of interest to Japan's en-route ATCOs, as it provides the opportunity for quantitative insights into the spatio-temporal distribution of the traffic-induced workload. These characteristics make T25 a suitable case for evaluating whether small lateral trajectory adjustments can reduce traffic-induced complexity.

For this application, 15 October 2019 was selected as the investigation day. Based on interviews with ATCOs, three operationally relevant time windows were identified from an expert perspective. These three samples capture distinct traffic patterns during peak arrival periods at RJTT within sector T25: a predominance of RJTT arrivals (07:00 - 08:00 JST), mutual interference between eastbound and westbound traffic flows (14:00 - 15:00 JST), and an increase in east-to-west traffic (18:00 -

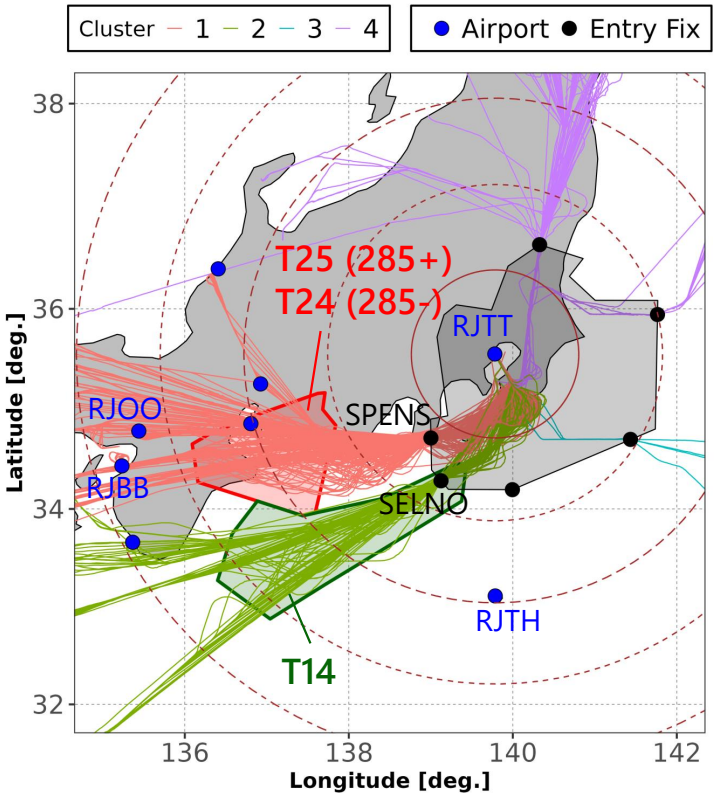


Figure 3 – Actual radar tracks color-coded with four colors according to the direction bound for RJTT in the northerly wind operation on a day in December 2019 [19]. Tokyo Approach Control Area is bounded by a black polygon with six entry fixes depicted with black dots. The radius of the brown dotted concentric circle is 50 NM centered on RJTT. The red polygon and green polygon show the en route sector in which the cruise speed control and the runway assignment decision are implemented. The blue dots indicate the airports located within 250 NM of RJTT. RJTT, Tokyo International Airport; RJOO, Osaka International Airport; RJBB, Kansai International Airport; and RJTH, Hachijojima Airport. T25 and T24 (red polygon) and T14 (green polygon), located between 150 NM - 200 NM from RJTT.

19:00 JST). Figure 4 illustrates the complexity profile of T25 over the entire day. The complexity curve shows pronounced morning and midday peaks, whereas the evening peak is less distinctly expressed in the daily aggregate profile.

5.1 Results

The complexity evaluation for sector T25 shows a consistent reduction in traffic complexity after applying the trajectory optimization. Across the three evaluated time windows, the mean complexity decreased in all cases. In the first window, the mean complexity was reduced from 5.5 to 4.8, corresponding to a reduction of 14%. The second window showed the strongest improvement, with a decrease from 7.2 to 5.4, equivalent to a 26% reduction. In the third window, the mean complexity decreased from 8.8 to 7.5, corresponding to a reduction of 15%. The maximum complexity was also reduced in all evaluated cases, with peak reductions of 15%, 6%, and 23%, respectively. The temporal development of the original and optimized complexity values is shown in Figure 6. At individual time steps, the optimized complexity drops to zero, as the lateral adjustment routes aircraft outside the sector boundary and the sector occupancy is thereby reduced to a single aircraft, for which the complexity metric evaluates to zero by construction.

The results indicate that the optimization not only lowers the average complexity level but also mitigates peak complexity situations. This is particularly relevant for operational air traffic management, where short periods of high complexity can strongly affect controller workload. The cumulative complexity over the sampled time steps decreased by 9.8, 23.9, and 16.6 complexity units for the three

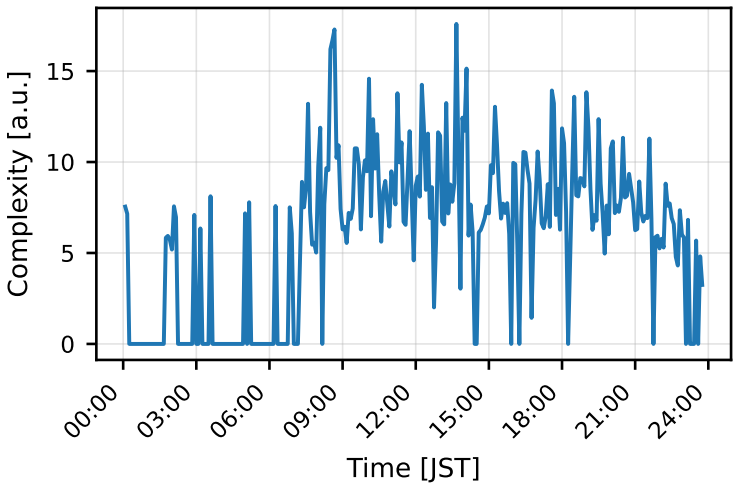
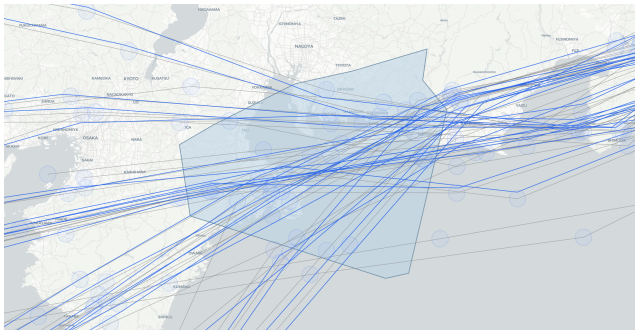
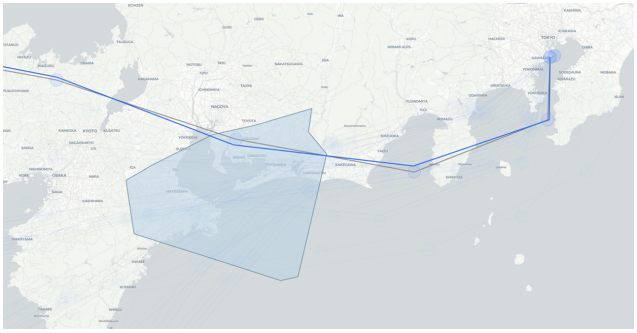


Figure 4 – Daily complexity profile of sector T25 under nominal traffic conditions. The time series shows sustained complexity throughout most of the day, with pronounced peaks in the early morning and around midday.



(a) Target sector T25 and flights through it from 07:00 to 08:00 JST.



(b) Visualization of the optimization from a single trajectory perspective.

Figure 5 – Screenshots from the browser-based trajectory visualization tool. The target sector T25 is shown as a light blue polygon. The blue lines represent optimized trajectories, while the grey lines indicate the original trajectories. The overlay of both line types enables a direct visual comparison of the route structures before and after optimization. The transparent circles mark radius areas around waypoints and visualize the spatial tolerance regions used by the optimization algorithm.

time windows, confirming that the improvement is visible over the entire evaluation interval and not only at isolated time points.

Additional traffic indicators support this interpretation. The minimum horizontal distance between aircraft increased after optimization in all three cases, from 0.61 NM to 0.96 NM, from 1.58 NM to 2.37 NM, and from 2.85 NM to 4.08 NM. The number of close aircraft pairs within 10 NM remained unchanged in two windows and decreased in the second window. This suggests that the optimization reduced complexity without worsening the evaluated horizontal proximity indicators. At the factor level, the largest reductions are mainly associated with structural and interaction-related complexity components, including STR, CP40, and CP70. These component-level changes are summarized in Figure 7.

5.2 Discussion

The results show that minor lateral trajectory adjustments reduce air traffic complexity in sector T25 across all three evaluated time windows. The reduction is observed both in the average complexity level and in the transient peaks, which indicates that the improvement is not limited to isolated time points.

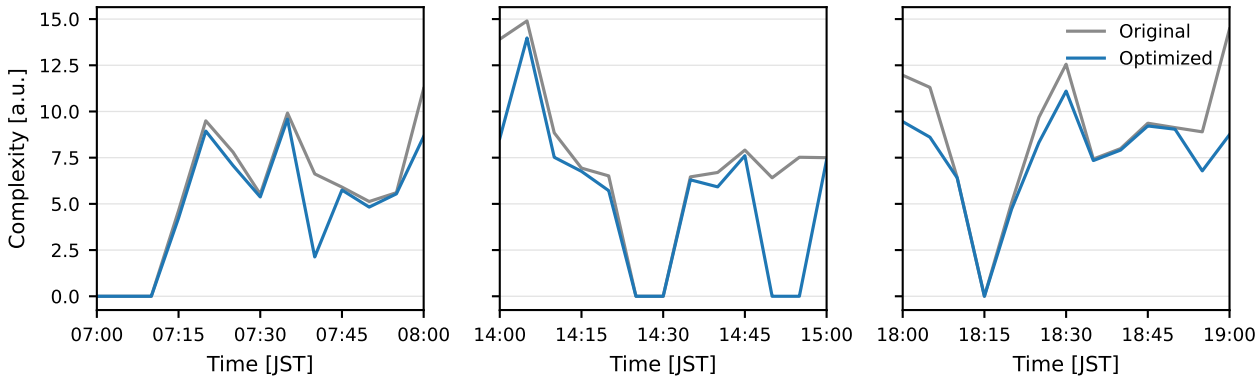


Figure 6 – Temporal comparison of sector complexity before and after trajectory optimization for T25. Dashed grey lines show the original trajectories, while solid blue lines show the optimized trajectories for the three evaluated time windows.

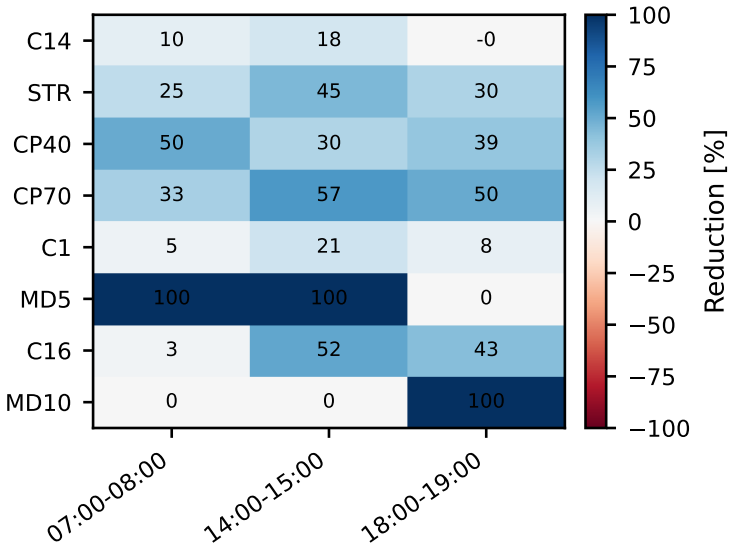


Figure 7 – Reduction of the main complexity factors after trajectory optimization in T25. The heatmap shows the percentage reduction for the factors with the largest absolute changes across the evaluated time windows, indicating which components contributed most strongly to the overall complexity decrease.

Traffic indicators suggest that this reduction is achieved without degrading horizontal proximity. The minimum horizontal distance between aircraft increases in all three windows, while the number of close aircraft pairs within 10 NM remains unchanged or decreases. This implies that the optimizer lowers complexity by reorganizing the lateral route structure. At the factor level, the largest reductions are associated with structural and interaction-related components, in particular traffic-flow alignment and predicted conflicts, indicating that the method addresses the geometric sources of complexity. Because segment lengths are preserved, these adjustments remain compatible with existing operational constraints.

These results extend prior work in two respects. First, the method has previously been evaluated only on simulated traffic [3], whereas the present study applies it to real surveillance data from Japanese CARATS data. Second, the method was originally developed for dynamic airspace concepts, whereas it is applied here within a conventional, statically sectorized airspace. The reductions obtained on real data, averaging 14-26%, fall within the same range as the 15-27% reported for the earlier simulation-based study [3], which indicates a transferability of the present approach.

However, the present findings are subject to limitations. The evaluation is restricted to three time

windows on a single day and to the single sector T25. Furthermore, the assessment relies on a complexity metric as a proxy for controller demand and does not include a HITL simulation, so the operational effect of the optimized trajectories on perceived workload remains to be confirmed.

6. Conclusion

This study applied a localized lateral trajectory adjustment method, integrated with GWO, to real surveillance data from Japanese airspace, and minimizing the complexity of sector T25 in the Fukuoka FIR. Three time windows, identified together with ATCOs as operationally relevant, were evaluated on a selected traffic day. This study yields the following key outcomes:

- Minor lateral trajectory adjustments reduced the mean air traffic complexity of sector T25 across all three evaluated time windows, with average reductions of 14-26% and peak reductions of up to 23%.
- The reduction was achieved without worsening horizontal proximity: the minimum horizontal distance between aircraft increased in all windows, while the number of close aircraft pairs within 10 NM remained unchanged or decreased.
- The reductions obtained on real data fall within the same range as those previously reported on simulated traffic, indicating a transferability of the method across both data sources and airspace configurations.

Future work should extend the evaluation to additional sectors and traffic days to strengthen statistical generalizability, and should conduct HITL experiments with ATCOs to assess the effect of the optimized trajectories on perceived workload.

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References

[1] D. Delahaye, S. Puechmorel, P. Tsiotras, et al. Mathematical models for aircraft trajectory design: A survey. In *Air Traffic Management and Systems*, pages 205–247, Tokyo, 2014. Springer Japan.

[2] Euclides Carlos Pinto Neto, Derick Moreira Baum, Jorge Rady de Almeida, et al. Deep learning in air traffic management (atm): A survey on applications, opportunities, and open challenges. *Aerospace*, 10(4), 2023.

[3] Simon Bruno Göppel, Ehsan Asadi, and Michael Schultz. Trajectory adjustments via grey wolf optimization to mitigate air traffic complexity in moving sectors. *Transportation Research Part C: Emerging Technologies*, 178:105176, 2025.

[4] Arnab Majumdar and Washington Y. Ochieng. Factors affecting air traffic controller workload: Multivariate analysis based on simulation modeling of controller workload. *Transportation Research Record*, 1788(1):58–69, 2002.

[5] Brian Hilburn. Cognitive complexity in air traffic control: A literature review. Technical report, EUROCONTROL, 2004.

[6] Richard H Mogford, Jerry A Guttman, SL Morrow, and P Kopardekar. The complexity construct in air traffic control: A review and synthesis of the literature, 1995. Technical Report DOT/FAA/CT-TN95/22, Federal Aviation Administration.

[7] Simon Bruno Göppel, Michael Schultz, and Eri Itoh. Complexity metrics for moving sectors. *IEEE Access*, 2024.

[8] Richard H. Mogford. Mental models and situation awareness in air traffic control. *The International Journal of Aviation Psychology*, 7(4):331–341, 1997.

[9] Parimal Kopardekar and Sherri Magyarits. Measurement and prediction of dynamic density. In *of the 5th USA/Europe Air Traffic Management R&D Seminar*, volume 139, 2003.

[10] Parimal H Kopardekar, Albert Schwartz, Sherri Magyarits, and Jessica Rhodes. Airspace complexity measurement: An air traffic control simulation analysis. *International Journal of Industrial Engineering: Theory, Applications and Practice*, 16(1):61–70, 2009.

[11] Judith Rosenow, Ehsan Asadi, Daniel Lubig, et al. Long range air traffic flow management with flight-specific flight performance. *Future Transportation*, 2(2):310–327, 2022.

[12] Junzi Sun. Openap.top: Open flight trajectory optimization for air transport and sustainability research. *Aerospace*, 9(7), 2022.

[13] Marianne Jacobsen and Ulf T. Ringertz. Airspace constraints in aircraft emission trajectory optimization. *Journal of Aircraft*, 47(4):1256–1265, 2010.

[14] S. Jain and P. Tsiotras. Multiresolution-based direct trajectory optimization. In *2007 46th IEEE Conference on Decision and Control*, pages 5991–5996, 2007.

[15] Jochen Rosenow, Markus Lindner, and Hartmut Fricke. Impact of climate costs on airline network and trajectory optimization: a parametric study. *CEAS Aeronautical Journal*, 8(2):371–384, 2017.

[16] Pierre Flener, Justin Pearson, Magnus Ågren, et al. Air-traffic complexity resolution in multi-sector planning. *Journal of Air Transport Management*, 13(6):323–328, 2007.

[17] Jonathan M. Histon. *The impact of structure on cognitive complexity in air traffic control*. PhD thesis, Massachusetts Institute of Technology, 2002.

[18] Seyedali Mirjalili, Seyed Mohammad Mirjalili, and Andrew Lewis. Grey wolf optimizer. *Advances in Engineering Software*, 69:46–61, 2014.

[19] Katsuhiro Sekine, Furuto Kato, Tomoaki Tatsukawa, Kozo Fujii, and Eri Itoh. Rule design for interpretable en route arrival management via runway-flow and inter-aircraft control. *IEEE Access*, 11:75093–75111, 2023.