

EVALUATING IMPACT OF INTERNATIONAL DEPARTURE TIME CONTROL ON DOMESTIC ARRIVAL DELAYS IN JAPAN USING MULTI-OBJECTIVE SIMULATION-BASED OPTIMIZATION

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Abstract

Growing air traffic demand and increasing international operations are placing pressure on domestic Air Traffic Flow Management (ATFM) systems, particularly in regions where dense domestic traffic networks interact with cross-border traffic flows. While previous studies have investigated airport-centric congestion mitigation and regional traffic flow harmonization, the downstream effects of international departure control on domestic arrival delays remain insufficiently quantified. This study investigates how departure time adjustments for international flights influence domestic arrival delays in Japan using a multi-objective simulation-based optimization framework. International departure timing control is modeled as minute-level time adjustments applied to flights operating under regional cross-border ATFM frameworks. A large-scale air traffic simulator based on a two-dimensional cellular automaton model is integrated with a genetic algorithm to optimize trade-offs between domestic delay mitigation and schedule perturbation minimization for controlled international flights. Simulation experiments are conducted using CARATS Open Data 2019 under high-demand traffic conditions within the entire Japanese airspace. The optimization results demonstrate that targeted departure time adjustments can reduce total domestic arrival delay by up to 26.7 hours (8.2%) while limiting schedule perturbation for controlled international flights. Origin-destination analysis additionally reveals heterogeneous delay reduction patterns across traffic groups. To evaluate operational feasibility, robustness analysis is performed using Monte Carlo simulations incorporating departure time execution uncertainty. Although uncertainty influences solution quality, many optimized solutions preserve substantial delay reduction benefits under realistic operational variability. These findings demonstrate the potential of international departure time control as a complementary mechanism for domestic delay mitigation and provide quantitative insights supporting future cross-border ATFM coordination.

Keywords: Air Traffic Flow Management; International ATFM; Simulation-Based Optimization; Arrival Delay Mitigation; Cross-Border Operations

1. Introduction

Air Traffic Flow Management (ATFM) is conducted to balance air traffic demand and available airport or airspace capacity to minimize delays and improve operational efficiency [1]. Traditionally, ATFM strategies have focused on delay reduction through measures such as Ground Delay Programs (GDP) and airborne delay absorption via aircraft speed control [2]. GDPs are widely used to regulate departure demand, while airborne delay absorption through speed adjustment is frequently employed to improve operational flexibility, particularly for long-haul operations [2].

However, cross-border traffic flow management introduces challenges beyond conventional domestic and regional ATFM. In Japan, long-term projections by the Japan Civil Aviation Bureau (JCAB) indicate substantial growth in international traffic and overflight operations by 2040, resulting in a larger

proportion of flights traversing multiple Flight Information Regions (FIRs) [3]. Since traffic interactions propagate beyond FIR boundaries, ATFM effectiveness increasingly depends on coordinated measures applied across broader traffic populations. ICAO Doc 9971 further states that ATFM is most effective when flow management measures apply to more than 70% of aircraft, suggesting that isolated single-FIR approaches may be insufficient and reinforcing the importance of regional coordination [4]. As international air transportation continues to expand globally, particularly in the Asia-Pacific region, effective ATFM across multiple regions is becoming increasingly important.

Regional approaches differ substantially. Europe employs a centralized coordination model via Network Manager from EUROCONTROL, whereas the Asia-Pacific region adopts a distributed multi-node collaborative framework because centralized international ATFM implementation is operationally difficult [5]. Collaborative initiatives such as ASEAN Multi-Nodal ATFM Collaboration (AMNAC) and North Asia Regional ATFM Harmonization Group (NARAHG) illustrate ongoing efforts toward international coordination [5]. AMNAC primarily employs airport-based departure flow control using Calculated Take-Off Time (CTOT) allocation, whereas NARAHG emphasizes cross-border flow harmonization through coordinated boundary crossing management such as Calculated Time Over (CTO) [6]. Traffic management actions implemented within one FIR can propagate downstream and generate knock-on effects across neighboring FIRs, requiring coordination beyond regional boundaries [5]. Moreover, long-haul international operations require flow management decisions several hours before aircraft reach constrained airspace, increasing sensitivity to operational uncertainty and making efficient inter-regional coordination increasingly challenging [7].

Recent ATFM studies have improved prediction capability, trajectory optimization, uncertainty management, and regional coordination mechanisms. Machine learning approaches have enhanced delay prediction and ATFM decision support [8, 9], while trajectory-based methods integrating speed control, rerouting, and delay absorption have improved operational efficiency under constrained traffic conditions [10, 11]. Uncertainty-aware optimization frameworks have further advanced capacity allocation, delay management, and operational robustness across airport and regional traffic systems [12, 13, 14, 15]. Cross-border coordination mechanisms have also been investigated to improve network-level traffic performance for long-range international operations [16, 17].

Existing studies have primarily focused on local traffic optimization, airport-level capacity balancing, uncertainty-aware ATFM design, and regional flow harmonization. While these approaches have substantially improved ATFM performance, relatively limited attention has been devoted to understanding how strategic international departure interventions propagate downstream and influence domestic network performance. This gap becomes increasingly important under heterogeneous regional ATFM frameworks, where independently managed flow-control measures may generate unintended network-wide effects.

Therefore, the objective of the current study is to investigate whether strategic international departure control can generate downstream domestic delay mitigation benefits through traffic propagation effects and and to provide quantitative insights relevant to future harmonization of heterogeneous regional ATFM frameworks. Using large-scale air traffic simulation combined with optimization and robustness evaluation under uncertainty, the study aims to quantify the operational effectiveness of international departure control as a cross-border ATFM strategy.

This paper is structured as follows. Section 2. describes the methodology, detailing the problem formulation, optimization objectives, and the airspace simulator used in this study. Section 3. outlines the data and simulation setup, which utilizes CARATS Open Data 2019. Section 4. presents the multi-objective optimization results, discussing the trade-offs between domestic arrival delay reduction and international departure time adjustments. Section 5. introduces a Monte Carlo-based robustness analysis to evaluate the impact of departure time execution uncertainty. Section 6. discusses the findings, including heterogeneous delay reduction mechanisms, practical deployment considerations, and limitations. Finally, Section 7. summarizes the conclusions and outlines future research directions.

2. Methodology

2.1 Operational Context and Problem Definition

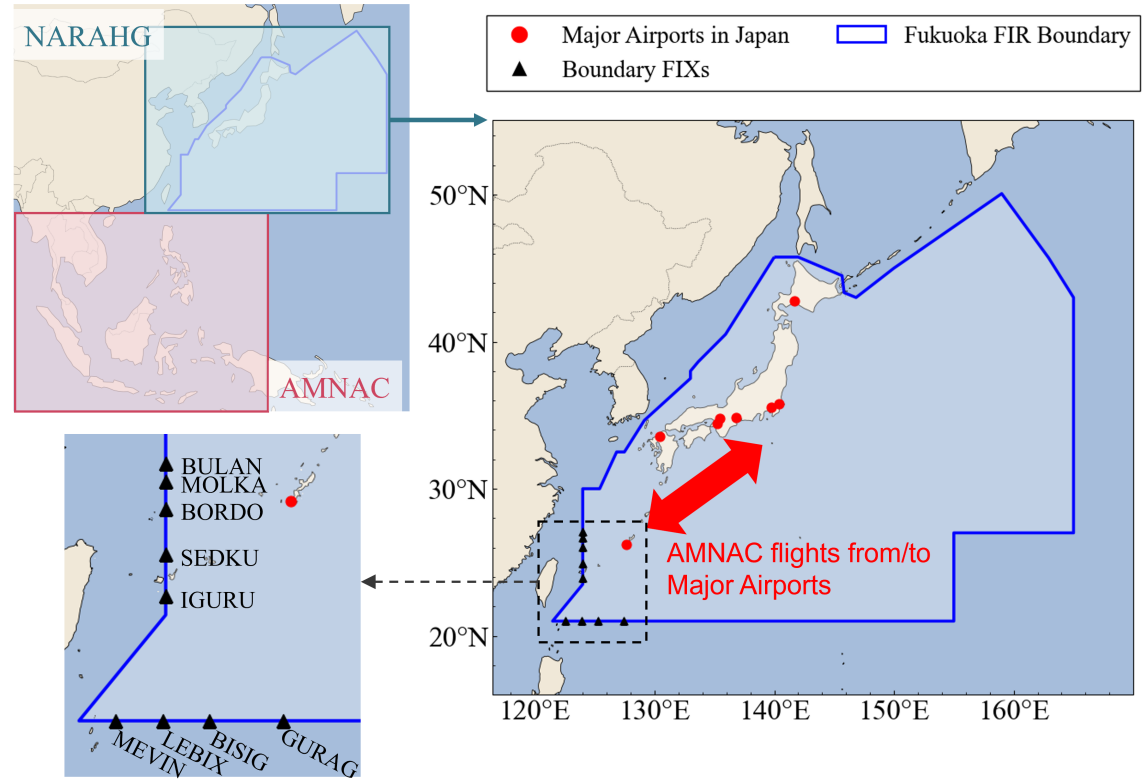


Figure 1 – Conceptual illustration of international and domestic traffic interactions within the Fukuoka FIR. Small departure time adjustments for AMNAC international flights alter downstream traffic patterns, resulting in different conflict resolution opportunities and arrival sequencing outcomes.

Figure 1 shows the operational environment considered in this study and the conceptual mechanism through which departure time control for AMNAC flights affects downstream domestic traffic performance.

This study focuses on international flights operating under the AMNAC framework, particularly traffic flows entering or exiting the Fukuoka FIR through major boundary FIX points such as BULAN and MOLKA. These international traffic streams coexist and interact with domestic traffic flows within the Japanese en-route airspace network, especially during peak arrival periods at major hub airports such as Tokyo Haneda (RJTT) and Narita (RJAA), where dense arrival and departure traffic interactions frequently occur.

Small temporal adjustments applied to international departures modify aircraft entry timing into constrained airspace regions. These changes propagate naturally through downstream traffic interactions, affecting aircraft occupancy patterns, spacing adjustment requirements, and arrival sequencing. In particular, international traffic streams entering through major boundary FIX points may temporally overlap with concentrated domestic arrival banks toward major hub airports such as Tokyo Haneda and Narita. Such overlap can increase merge-point interactions and terminal-area congestion, requiring additional spacing adjustments and conflict resolution actions. As illustrated in Fig. 1, even modest timing adjustments introduced at FIR boundary entry points may alter congestion conditions around major terminal areas.

This propagation mechanism creates opportunities to improve domestic arrival performance through international departure time control. However, only international flights operating on AMNAC target routes are considered controllable decision variables in this study. Let I denote the set of all AMNAC flights entering and exiting the Fukuoka FIR subject to departure time adjustment and D represent the domestic flights. Domestic flights and non-target international flights remain operationally unconstrained and are simulated as background traffic affected indirectly through downstream traffic

interactions.

2.2 Multi-Objective Optimization Formulation

The optimization problem is formulated with two objectives. The first objective minimizes the total domestic arrival delay, defined as the sum of positive deviations between actual and scheduled arrival times for all domestic flights. Let D denote the set of domestic flights, ATA_i the actual arrival time of flight i, and STA_i its scheduled arrival time. The objective is expressed as

$$\min f_1 = \sum_{i \in D} \max\left(\mathrm{ATA}_i - \mathrm{STA}_i, 0\right). \tag{1}$$

The second objective represents schedule perturbation for AMNAC flights subject to control. Let I denote the set of AMNAC international flights and t_j the time offset applied to flight j, defined as an adjustment to the Fukuoka FIR entry time for inbound flights and as a departure time adjustment at the origin airport for outbound flights. Schedule perturbation is defined as the aggregated relative magnitude of departure time adjustments normalized by the scheduled flight duration within the Fukuoka FIRST_j:

$$\min f_2 = \sum_{j \in I} \frac{|t_j|}{\mathrm{ST}_j}. \tag{2}$$

This normalization prevents long-haul flights from being disproportionately penalized relative to short-haul operations and enables fair comparison across heterogeneous international routes. This design also prevents disproportionate penalization of long-haul flights and aligns schedule perturbation evaluation with relative operational burden. Departure time offsets t_j are treated as discrete design variables bounded within a realistic operational range of -5 to $+15$ minutes. The range was selected to reflect operationally feasible strategic ATFM interventions while avoiding excessive schedule disruption. The asymmetric range reflects practical ATFM operations, where departure holding is operationally more feasible than departure advancement.

Only AMNAC flights are included in the control set, while domestic flights and flights managed under NARAHG, the regional ATFM framework to which Japan belongs, are excluded from direct control. This modeling choice reflects current operational practices and ensures consistency with realistic cross-border ATFM constraints.

2.3 Simulation-Based Multi-Objective Optimization Framework

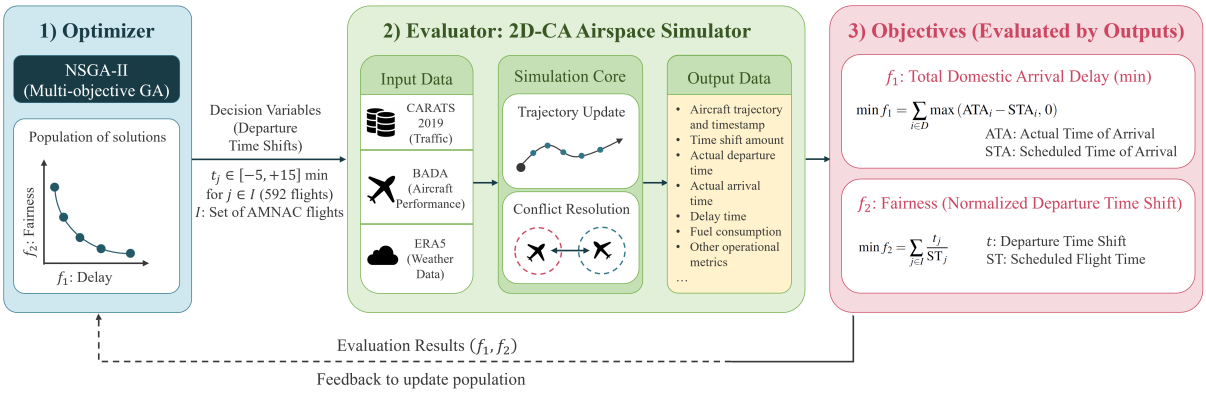


Figure 2 – Overall simulation-based multi-objective optimization framework integrating NSGA-II and the 2D cellular automaton airspace simulator. Departure time adjustments are optimized iteratively through feedback between the optimizer and simulator outputs.

Figure 2 illustrates the proposed simulation-based multi-objective optimization framework, which integrates a traffic flow optimizer with a high-fidelity airspace simulator. The framework aims to identify appropriate international departure time control strategies while explicitly capturing downstream traffic interactions and operational constraints.

On top of the simulator, a multi-objective genetic algorithm, Non-dominated Sorting Genetic Algorithm II (NSGA-II) [18], is employed to explore trade-offs between operational efficiency and schedule perturbation in AMNAC departure time control. The optimizer generates candidate solutions consisting of departure time adjustment values t_j for controlled international flights $j \in I$, where allowable adjustments are constrained within operationally feasible bounds. Each candidate solution is subsequently evaluated through airspace simulation to estimate its system-wide operational impacts. Population size, crossover parameters, and mutation parameters are summarized in Section 3..

2.4 Airspace Simulation Model: Two Dimensional (2D) Cellular Automaton (CA) Simulator

Air traffic dynamics are modeled using a validated high-fidelity en-route airspace simulator based on a two-dimensional cellular automaton (CA) framework developed in previous work [19]. The simulator is designed to reproduce large-scale traffic interactions while maintaining computational scalability suitable for simulation-based optimization involving hundreds of control variables and thousands of aircraft trajectories. This simulator has been previously validated against operational traffic data and demonstrated sufficient fidelity for reproducing traffic interaction dynamics relevant to delay propagation analysis. Validation results confirmed that the simulated flight-time distributions toward major airports reproduced both the observed peak structure and distribution spread found in operational traffic data. In addition, locations where spacing adjustments frequently occurred in the simulation showed substantial agreement with operational radar-vectoring areas, indicating that the simulator appropriately captures major traffic management behaviors and congestion patterns observed in real operations.

The airway structure is discretized into horizontal cells and flight levels, where aircraft movements are propagated sequentially with a temporal resolution of one second. Aircraft performance characteristics, including speed profiles and flight envelope constraints, are derived from the EUROCONTROL Base of Aircraft Data (BADA) model [20]. Meteorological impacts are incorporated using ERA5 atmospheric reanalysis data [21] to account for wind-induced trajectory variations and operational disturbances.

Aircraft trajectories are generated along representative routes extracted from operational flight data and updated dynamically throughout the simulation. When predicted aircraft separation falls below operational requirements, conflict resolution mechanisms are activated to restore safe spacing conditions.

Traffic interactions resulting from departure time control propagate naturally through the simulation environment. Small temporal changes introduced at departure airports or FIR boundary entry or exit points alter aircraft occupancy patterns within constrained sectors, potentially affecting spacing adjustment requirements and downstream arrival sequencing. Consequently, domestic arrival delay emerges endogenously from aircraft interactions rather than being explicitly imposed by predefined delay models.

Simulation outputs are subsequently evaluated using the objective functions defined in Eqs. (1) and (2), representing domestic arrival delay reduction and schedule perturbation of departure time adjustments, respectively. The evaluated objective values are then returned to NSGA-II, which iteratively updates candidate solutions to approximate the Pareto-optimal front. Through repeated optimization and simulation cycles, the framework identifies departure control strategies that balance domestic arrival delay reduction and departure time adjustment perturbations while explicitly accounting for traffic propagation effects and airspace interactions.

3. Data and Simulation Setup

The simulation experiments are conducted using CARATS Open Data 2019, which provides detailed flight trajectory and schedule information for air traffic operations in Japan. October 15, 2019, a representative high-demand day in 2019 is selected from upper traffic-volume percentile for analysis to capture typical congestion patterns under normal operational conditions. Actual recorded departure and arrival times are used as the baseline schedule in the simulation, ensuring that the traffic demand and temporal distribution of flights closely reflect real-world operations. The simulation domain covers the entire Fukuoka Flight Information Region (FIR), encompassing both domestic and international operations, with a total of 4,681 flights included in the simulated traffic sample.

The airspace simulation is configured to represent realistic operational constraints in both en-route and terminal airspace. Standard separation requirements of 7 NM in en-route airspace and 4 NM in terminal maneuvering areas are applied throughout the simulation. Aircraft movements are propagated with a temporal resolution of one second. The resulting optimization problem includes 592 international AMNAC flights as decision variables, each associated with a discrete departure time offset.

The multi-objective optimization was performed using NSGA-II with a population size of 1000 and 1000 generations. Preliminary experiments confirmed that smaller population sizes frequently converged to locally clustered Pareto fronts because of the high-dimensional search space involving 592 control variables. Optimization terminated after 1000 generations without further convergence improvement. Convergence trends are omitted due to space limitations. Simulated binary crossover (SBX) and polynomial mutation were employed with crossover probability $p_{cross} = 1.0$, crossover distribution index $\eta_c = 20$, and mutation distribution index $\eta_m = 20$. Due to the large computational demand associated with evaluating traffic interactions in large-scale airspace simulations, optimization experiments were conducted using the Fugaku supercomputer. The computation employed 250 compute nodes for approximately 216 hours. Each node consisted of 48 CPU cores, and parallel computation was implemented using a hybrid MPI–OpenMP parallelization framework. This computational scale highlights the importance of high-performance computing for large-scale simulation-based optimization involving thousands of traffic interactions and hundreds of control variables.

4. Optimization Results

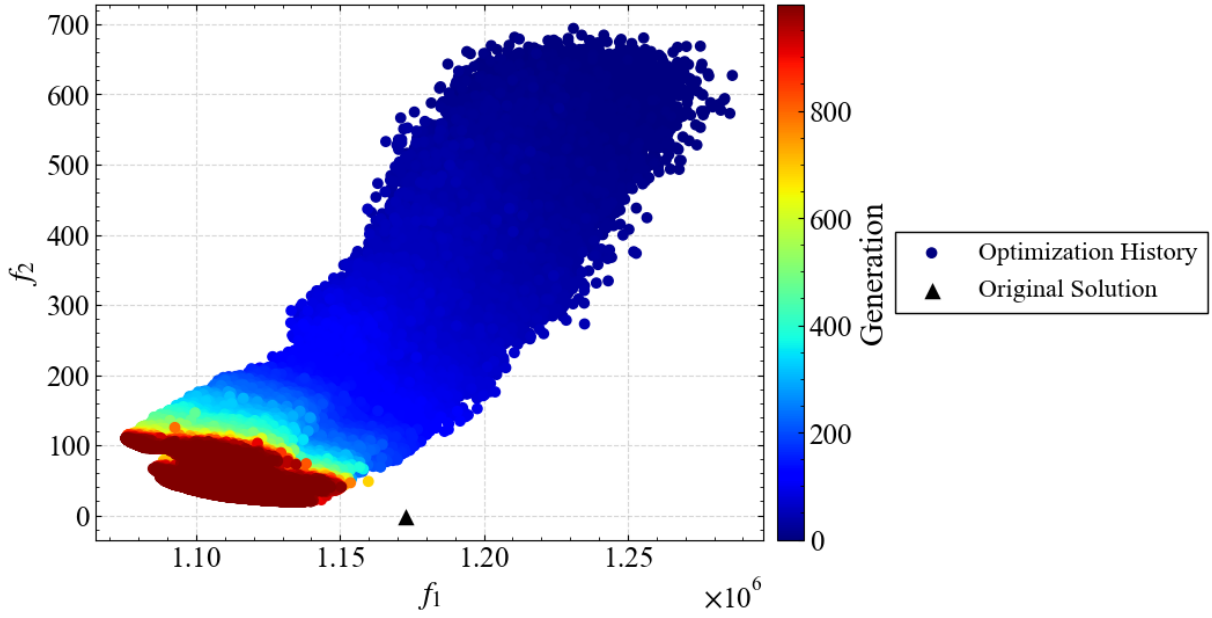


Figure 3 – Pareto front obtained from the multi-objective optimization. Each point represents a feasible solution evaluated during the optimization process, while the baseline solution corresponds to the original traffic schedule without international departure time control.

Figure 3 presents all feasible solutions evaluated by NSGA-II, as well as the baseline solution corresponding to the original traffic schedule without international departure time control. The optimization results reveal a clear trade-off between improving domestic arrival performance and imposing departure time adjustments on international operations.

Compared with the baseline scenario without international departure time control, the optimized solutions achieve a maximum reduction of 96,240 s, corresponding to 26.7 h, in total domestic arrival delay. This corresponds to approximately 8.2% of total domestic arrival delay (1,173,010 s), compared with the baseline scenario while keeping most departure adjustments within several minutes. Although the average per-flight delay reduction is modest, cumulative system-wide effects become operationally significant because of the large number of domestic flights affected simultaneously.

These results indicate that selectively allocated departure time adjustments can yield system-wide benefits for domestic operations while limiting the magnitude of schedule perturbations imposed on international flights.

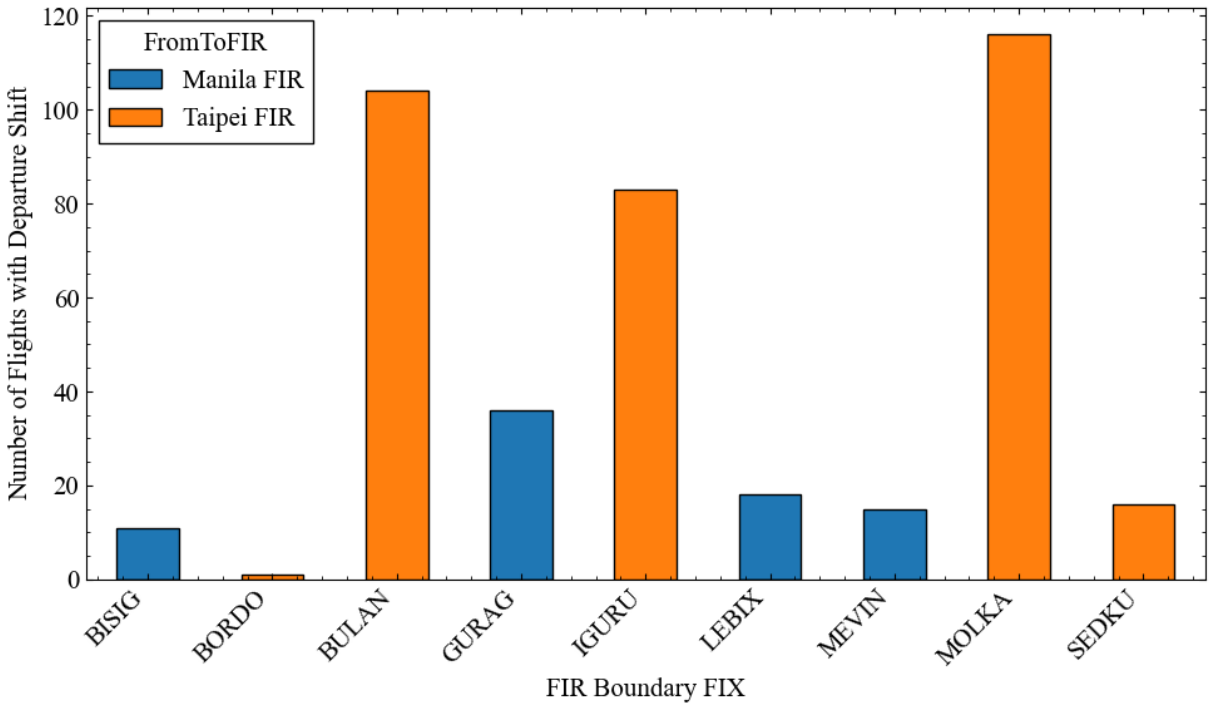


Figure 4 – Number of international flights with optimized departure time adjustments, grouped by FIR boundary FIX and associated FIR flow. The results indicate that departure shifts are concentrated on specific international traffic streams rather than uniformly distributed across all flights.

Figure 4 shows the number of international flights whose departure times were adjusted by the optimization, categorized by FIR boundary FIX and associated FIR flows. The results indicate that departure shifts were not uniformly distributed across all international flights. Instead, the optimization concentrated adjustments on a limited subset of flights, suggesting that the proposed framework selectively identifies flights with greater influence on downstream traffic conditions. In particular, flights associated with the Taipei FIR, especially those passing through BULAN, IGURU, and MOLKA, appear more frequently among the adjusted flights than other boundary flows. These traffic streams temporally overlap with dense domestic arrival banks toward Tokyo metropolitan airports, increasing their influence on downstream sector occupancy and arrival sequencing complexity. This tendency suggests that these international traffic streams may provide greater leverage for mitigating downstream domestic congestion and balancing sector demand.

Figure 5 shows the distribution of optimized departure time adjustments assigned to international flights for each FIR boundary FIX. Overall, the assigned departure shifts remain moderate, with most mean and median values located within approximately 0–2 minutes. This indicates that the proposed optimization framework does not require substantial schedule modifications for the majority of international flights. However, several FIR boundary FIXs, particularly BULAN, IGURU, and MOLKA, exhibit positively skewed distributions with larger upper tails. These boundary flows interact strongly with dense arrival streams toward major hub airports, increasing their influence on downstream congestion formation. These observations suggest that while most flights receive relatively small adjustments, a limited number of flights are assigned larger departure shifts.

Figure 6 presents an origin–destination analysis of domestic arrival delay reduction, revealing heterogeneous mitigation effects across different city pairs. Further origin-destination analysis indicates that the effectiveness of international departure control is highly heterogeneous. Short-haul domestic flows, such as RJFF (Fukuoka) – RJOM (Matsuyama), exhibit large per-flight delay reductions

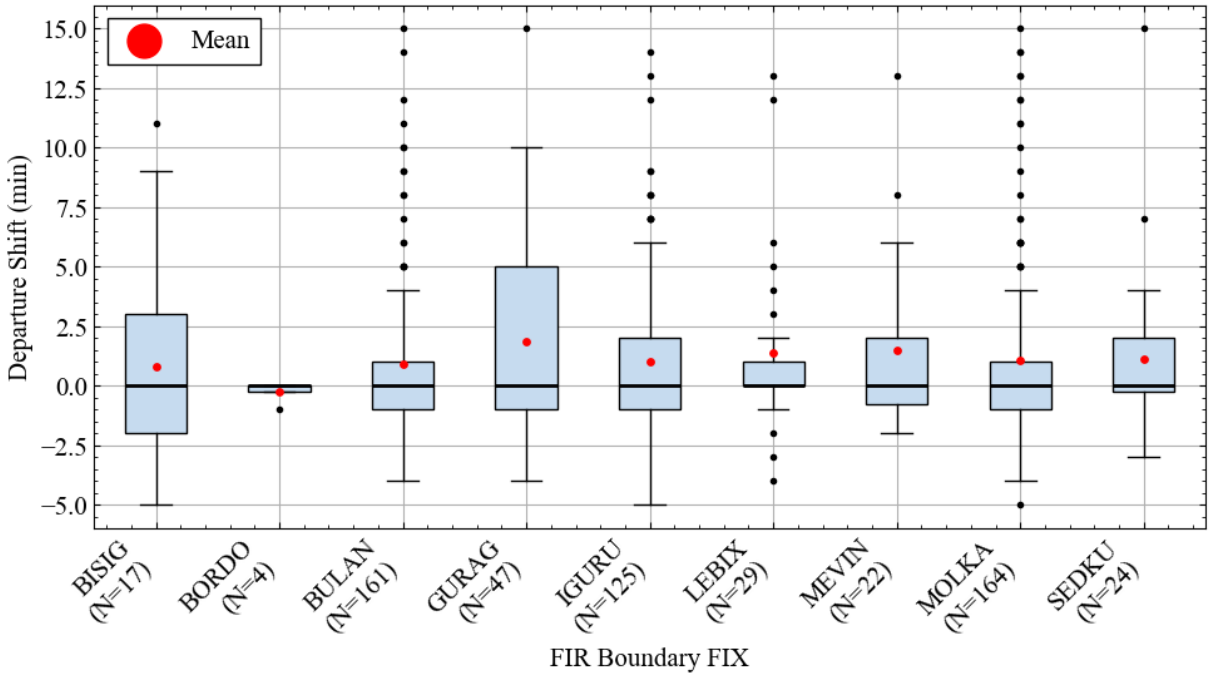


Figure 5 – Distribution of optimized departure time adjustments for international flights by FIR boundary FIX. Red markers indicate mean values, and boxplots show the distribution of assigned departure shifts.

(approximately 15 minutes) potentially because short-haul regional operations are more sensitive to upstream traffic interactions. In contrast, hub-bound flows to major airports (RJTT, RJAA, ROAH: Naha) show smaller per-flight gains (1–5 minutes) but generate large aggregate benefits due to high traffic volumes.

5. Robustness Analysis

The optimization results presented in the previous section were obtained under deterministic assumptions, where all departure time adjustments are assumed to be implemented exactly as optimized. In practical operations, however, departure time control cannot always be executed without deviation. Aircraft departure timing is influenced by various operational factors, including airport surface congestion, airline operational constraints, and uncertainty in air traffic management execution. Consequently, the actual implementation of optimized departure schedules may differ from their planned values.

Such implementation uncertainty is particularly relevant for the present study because the proposed framework relies on minute-level timing adjustments of international flights to improve downstream domestic arrival performance. If small deviations from the optimized schedule substantially degrade system performance, deterministic optimal solutions may have limited operational applicability. Therefore, evaluating robustness against execution uncertainty is essential for assessing the practical feasibility of international departure time control strategies.

To investigate this aspect, a Monte Carlo–based robustness evaluation framework is introduced. Random perturbations are applied to optimized departure control solutions, and the resulting traffic scenarios are re-simulated using the airspace model developed in this study. By evaluating how domestic arrival delay performance changes under uncertainty, the analysis aims to identify whether Pareto-optimal solutions remain effective when realistic implementation variability is considered.

5.1 Monte Carlo Setup

To evaluate robustness against implementation uncertainty, Monte Carlo simulations are conducted by introducing stochastic perturbations to Pareto-optimal departure control solutions obtained from the multi-objective optimization framework.

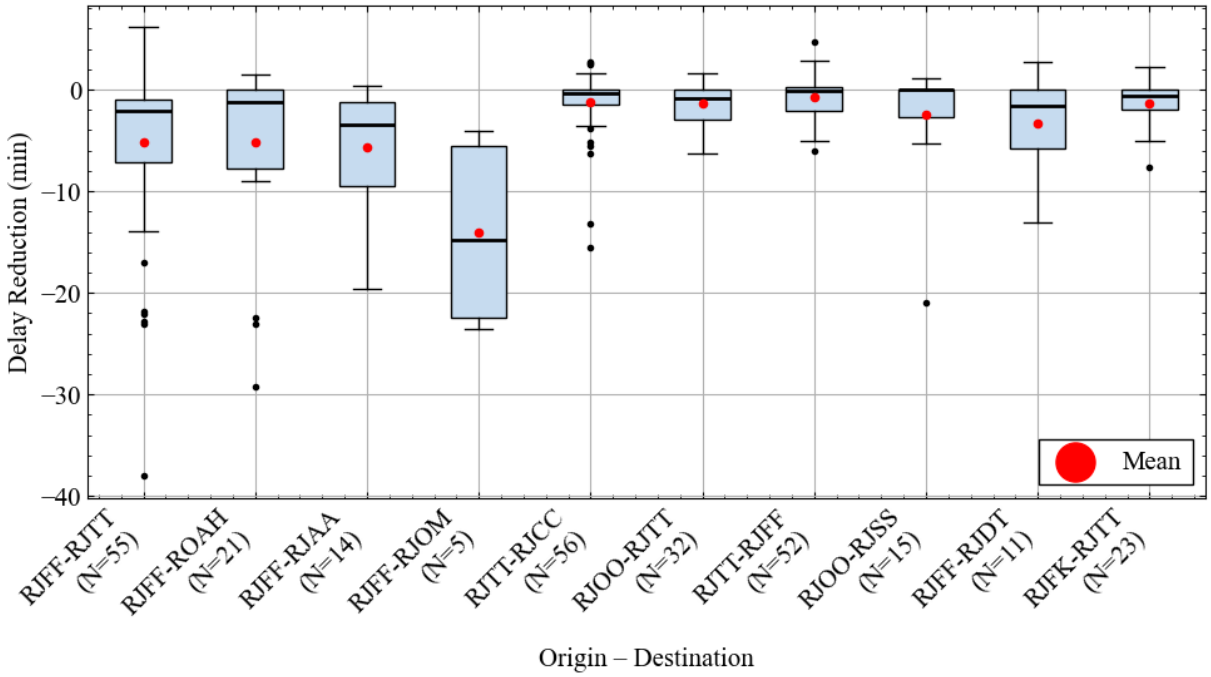


Figure 6 – Domestic arrival delay reduction for different origin–destination groups. The groups are ordered from left to right by decreasing total domestic arrival delay reduction.

Let

$$\mathbf{x} = (x_1, x_2, \ldots, x_d) \tag{3}$$

denote an optimized departure control solution, where d represents the number of controlled international flights and each design variable corresponds to the departure time adjustment assigned to an individual flight.
Execution uncertainty is modeled by independently adding Gaussian perturbations to each design variable. For Monte Carlo sample k, a perturbed solution $\tilde{\mathbf{x}}^{(k)}$ is generated as

$$\tilde{\mathbf{x}}^{(k)} = \mathbf{x} + \boldsymbol{\varepsilon}^{(k)} \tag{4}$$

where

$$\boldsymbol{\varepsilon}^{(k)} \sim \mathcal{N}\left(\mathbf{0}, \sigma^2 \mathbf{I}\right) \tag{5}$$

and σ represents the standard deviation of departure time execution uncertainty.
The optimization framework discretizes the departure time control variables into one-minute intervals. Therefore, perturbed solutions are projected back to the feasible discrete design space before simulation:

$$\mathbf{x}^{(k)} = \text{map_to_discrete}\left(\tilde{\mathbf{x}}^{(k)}\right) \tag{6}$$

The baseline robustness evaluation adopts $\sigma = 2$ min, corresponding to operational variability in departure time execution. To evaluate robustness under operational uncertainty, Monte Carlo simulations are conducted using the 81 Pareto-optimal solutions obtained from the optimization. For each solution, $N = 100$ stochastic samples were generated by incorporating operational variability, resulting in a total of 8,100 simulation runs.
The resulting distributions of objective function values are analyzed to quantify sensitivity to implementation uncertainty and to identify Pareto-optimal solutions that maintain performance under realistic operational variability.

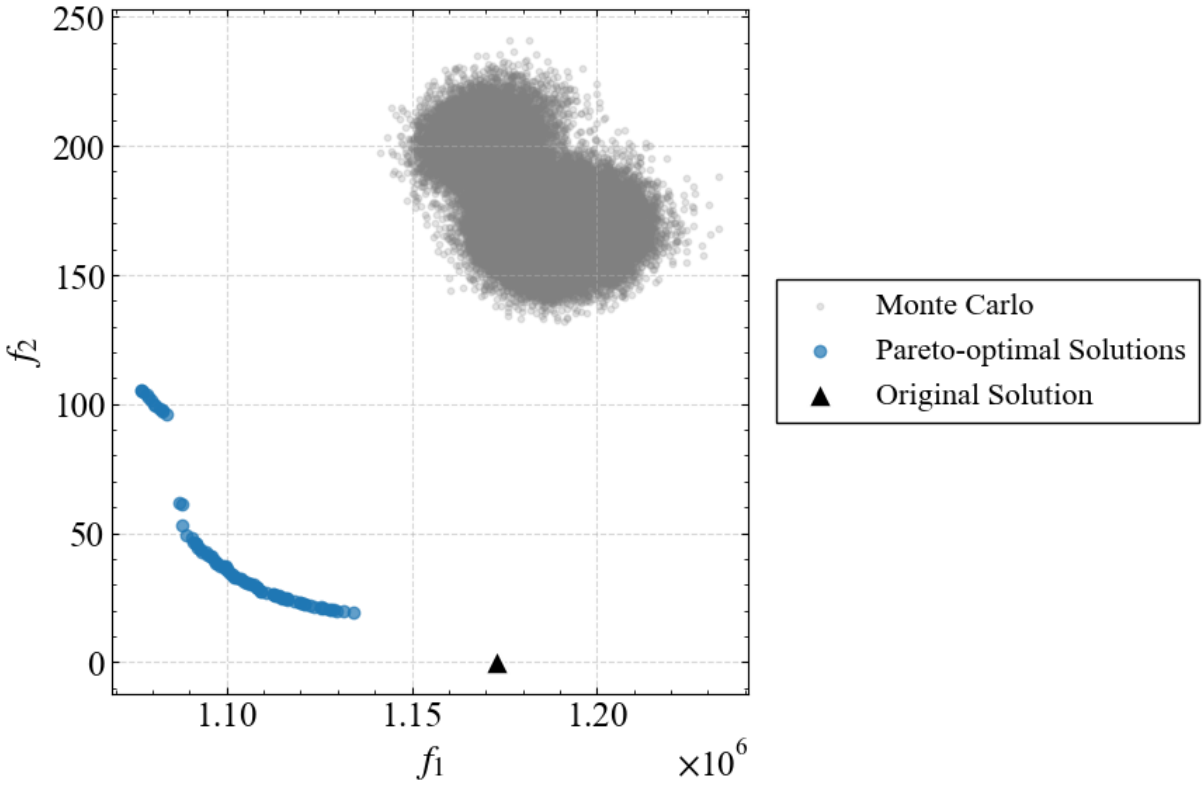


Figure 7 – Monte Carlo robustness analysis under departure time uncertainty ($\sigma = 2$ min). Blue markers indicate Pareto-optimal solutions obtained by deterministic optimization, while gray markers represent Monte Carlo simulation outcomes considering stochastic departure perturbations.

5.2 Robustness Results

Figure 7 presents the Monte Carlo simulation results used to evaluate the robustness of the optimized departure control strategy under departure time uncertainty. In the simulation, departure uncertainty is modeled as an independent Gaussian perturbation with a standard deviation of 2 minutes, representative operational departure execution uncertainty reported in prior literature [12]. Under this assumption, approximately 68% of flights deviate within ± 2 minutes and approximately 95% within ± 4 minutes, representing realistic operational variability. Compared with the original uncontrolled baseline, approximately 40% of simulation samples achieve lower total delay, whereas approximately 60% result in higher delay values. These results indicate that the effectiveness of the proposed departure control strategy is sensitive to operational uncertainty, and performance improvements achieved in deterministic optimization are not always preserved under stochastic conditions. Although performance degradation was observed in many stochastic realizations, a substantial subset of optimized solutions preserved meaningful delay reduction benefits under realistic operational variability. These findings indicate that robustness-aware optimization may provide greater practical applicability than deterministic optimization alone.

6. Discussion

6.1 Effectiveness of International Departure Time Control

The optimization results demonstrated that minute-level departure time adjustments applied to international flights can significantly improve domestic arrival performance. The Pareto-optimal solutions revealed a clear trade-off between domestic arrival delay mitigation and schedule perturbation minimization for international operations. The previous study [12] also indicates that system-wide benefits can be achieved without imposing excessive operational burden on controlled flights.

As shown in Fig. 3, the maximum reduction of 26.7 hours (8.2%) in total domestic arrival delay suggests that relatively small timing modifications to international traffic can propagate downstream and influence congestion formation within domestic airspace. These effects emerge because departure

timing changes alter aircraft occupancy patterns within constrained sectors especially in terminal maneuvering area of hub airports, affecting spacing adjustment requirements and conflict resolution processes throughout the traffic network.
Furthermore, departure time adjustments were not distributed uniformly across controlled international flights (see Fig. 4 and 5). Instead, the optimization selectively assigns larger adjustments to a limited subset of flights, while most flights receive relatively small schedule modifications. This observation suggests that domestic delay propagation is disproportionately influenced by specific traffic interactions and that targeted intervention strategies may provide substantial operational benefits without requiring widespread schedule modifications.

6.2 Heterogeneous Delay Reduction Mechanisms

The origin-destination analysis (see Fig. 6) revealed that delay reduction effects are not uniformly distributed across traffic flows. Some domestic routes exhibited substantial per-flight delay reductions, whereas others produced relatively modest improvements despite contributing significantly to total system-level performance. These results are consistent with recent studies on multi-airport systems showing that schedule displacements are not evenly distributed across arrival and departure flows, as individual flight adjustments must simultaneously satisfy both airport and fix-level capacity constraints [13].
Short-haul domestic operations showed relatively large per-flight improvements, indicating that small changes in upstream traffic conditions can strongly influence tightly connected regional traffic flows. In contrast, hub-bound traffic toward major airports generated smaller delay reductions on an individual flight basis but produced substantial aggregate benefits because of high traffic concentration.
These observations suggest that delay mitigation mechanisms operate through complex network interactions rather than direct one-to-one relationships between controlled international flights and affected domestic operations. International departure timing adjustments influence sector occupancy patterns, traffic synchronization, and congestion formation processes, which subsequently propagate through downstream traffic networks. This propagation behavior is consistent with slot-assignment chain reactions reported in previous studies [9], where minor modifications to one flight's timing trigger network-wide interactions and alter downstream spatio-temporal resource availability for subsequent operations.. Consequently, identifying critical traffic groups that disproportionately contribute to delay propagation represents an important direction for future operational design.

6.3 Robustness and Practical Deployment

The robustness evaluation demonstrated that uncertainty in departure time execution under $\sigma = 2$ min can influence operational effectiveness of optimized solutions as shown in Fig. 7. Although many Monte Carlo realizations preserved beneficial delay reduction effects relative to the baseline schedule, performance degradation was also observed in a subset of scenarios.
These results indicate that deterministic optimality does not necessarily guarantee operational robustness. Comparative evaluations between robust and deterministic frameworks in the literature [12] confirm that solutions optimized for nominal conditions exhibit significantly higher sensitivity to execution errors, often resulting in performance outcomes that are inferior to robust alternatives when subjected to stochastic perturbations. Solutions achieving aggressive delay reduction under ideal execution conditions may become sensitive to implementation uncertainty because delay mitigation effects partially depend on maintaining carefully coordinated traffic timing relationships within congested sectors.
Nevertheless, approximately 40% of optimized solutions maintained favorable performance characteristics under stochastic perturbation, suggesting that international departure time control possesses operational potential even when realistic implementation variability is considered. Quantitative assessments of departure timing uncertainties in the previous study [15] further suggest that maintaining operational predictability requires dynamically adjusting control parameters to account for execution errors, as higher levels of implementation noise necessitate more conservative strategies to prevent capacity losses. These observations emphasize the importance of incorporating uncertainty explicitly into future optimization frameworks and suggest that operational deployment should balance delay reduction performance with robustness considerations.

6.4 Strengths and Limitations

The present study contributes a quantitative framework for evaluating interactions between international departure control and domestic arrival delay performance using large-scale simulation-based optimization. Unlike previous studies that primarily evaluate airport-level operational metrics or regional flow stability, the proposed approach explicitly captures downstream delay propagation effects within interconnected traffic networks. Note that the present simulator focuses primarily on en-route traffic interactions and simplified conflict resolution behaviors, and therefore does not fully reproduce controller tactical decision-making or detailed terminal-area operations. Furthermore, the robustness evaluation extends the analysis beyond deterministic optimization and improves practical relevance. Although multiple uncertainty levels would provide a more comprehensive characterization of robustness behavior, computational resource constraints limited the present analysis to a representative operational variability scenario ($\sigma = 2$ min).

However, several limitations should also be acknowledged.

First, the present analysis focuses on a representative high-demand day and therefore does not fully capture variability associated with different traffic patterns, meteorological conditions, and operational environments. Previous studies have shown that weather-related factors strongly influence flow regulation occurrence and severity, suggesting that broader multi-day analyses are necessary to evaluate generalizability [8].

Second, uncertainty representation remains simplified. Long-range international operations involve uncertainty in demand prediction, weather evolution, trajectory adherence, and sector capacity estimation. Forecast errors and dynamically changing operational conditions may influence the effectiveness of departure control strategies and reduce operational predictability.

7. Concluding Remarks

This study investigated the impact of international departure time control on domestic arrival delays in Japan through a multi-objective, simulation-based optimization approach. Focusing on 592 international flights operating under the AMNAC framework, departure time adjustments were systematically optimized to minimize total domestic arrival delay while accounting for schedule perturbation minimization for AMNAC international operations. The results demonstrated that relatively small and targeted adjustments to international departure times can lead to a maximum reduction of 26.7 h in domestic arrival delays. Furthermore, the origin–destination analysis indicated that specific international traffic groups provide disproportionately large benefits relative to the operational burden imposed. Monte Carlo simulations demonstrated that performance benefits were partially preserved under operational uncertainty. These findings highlight the potential of international departure time control as a promising complement to existing domestic or regional ATFM measures and provide quantitative evidence supporting future harmonization among heterogeneous regional ATFM frameworks operating across interconnected international traffic networks.

Future work should investigate how heterogeneous regional ATFM frameworks can be harmonized to enable effective inter-regional traffic management as international traffic continues to grow. Particular attention should be given to interoperability among regional ATFM systems, collaborative information-sharing mechanisms, and long-term airspace demand forecasting capabilities needed to support strategic and tactical decision-making under uncertainty. These efforts will support the evolution of scalable and collaborative international ATFM systems.

Acknowledgement

This work was supported in part by JSPS KAKENHI under Grants 24KK0088 and 25K23471, and in part by MEXT through the Program for Promoting Researches on the Supercomputer Fugaku. Computational resources were provided by the Fugaku Supercomputer at the RIKEN Center for Computational Science (Project ID: hp250221) under Grant JPMXP1020230215. The authors would also like to thank JCAB for providing CARATS Open Data.

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