Devising Strategies for Aircraft Arrival Processes via Distance-based Queuing Models

Eri Itoh[*,†], Michael Schultz[‡], Srinivas Athota[§], Vu Duong[§]

[*] Department of Aeronautics and Astronautics, The University of Tokyo, Tokyo, Japan

[†] Air Traffic Management Department, Electronic Navigation Research Institute, Tokyo, Japan

[‡]Institute of Logistics and Aviation, Technische Universität Dresden, Dresden, Germany

[§] Air Traffic Management Research Institute, Nanyang Technological University, Singapore

***Abstract*—Accommodating highly-frequented air traffic at an airport, managing aircraft arrivals is one of the most important functions in the operation. This paper introduces distance-based queuing models, which enable us to present aircraft arrival processes in accordance with the distance at the destination airport, and estimates bottlenecks and delay time in the current and future arrival traffic flows. Strategies to optimize aircraft arrival processes are discussed based on the proposed models applying for two case study airports, Tokyo International Airport and Singapore Changi International Airport. Stochastic parameters in the models are identified using large volume of flight plan and track data-sets, including actual radar data and ADS-B data. Analyzing different features of arrival process at the case study airports provides insights into arrival control strategies and contributes to establish systematic approaches for designing arrival management for long-range traffic flows.**

***Keywords*—queuing theory, data science, arrival traffic management, Singapore Changi International Airport, Tokyo International Airport, ADS-B data**

I. Introduction

The management of aircraft arrivals at airports is central to airport operations. In the United States, Traffic Management Advisory (TMA) [1] was deployed in air traffic control centers in the 1990's, while its enhanced version, Time-Based Flow Management (TBFM) [2] and Terminal Sequencing and Spacing (TSAS) [3], takes into account future airborne-based operations, so called Flight-deck Interval Management (FIM) [4] which is an application using ADS-B input and output information on board. These systems consist of air-ground cooperation contribute to sequencing and time-spacing of the arrival traffic consistently in the en-route and terminal airspace areas. In Europe, SESAR projects have facilitated collaboration among European countries and contributed to the uncertainty handling and trajectory synchronization in the automated arrival management [5] as well as to the development of "Enhanced" Arrival Management (AMAN), which coordinates the arrival time-schedules covering wider ranges of airspace than in the case of conventional operations [6].

In Asia-pacific, targeting strategic air traffic flow management, Long-Range Air Traffic Flow Management (LR-ATFM) has been devised to provide a basis for research into applications beyond current system time-frames [7]. On-going Japanese research and development on the "Extended" AMAN (E-AMAN) aims to ensure efficient arrival traffic flow at Tokyo International Airport [8], [9]. In the E-AMAN scheme, arrival traffic flow control, which coordinates traffic volume under limited airspace capacity and runway throughput, shifts to time-based operations close to the destination airports, which ensures minimum time-spacing between arrivals. An efficient transition from flow control to time-based operations depends on the characteristics of the arrival air traffic flow and its surrounding environment, such as, the runway and airspace capacity, weather conditions, air routes or geographical constraints. One of the most important requirements for the design of future Air Traffic Management (ATM) system is to accommodate an increase of 250% in the global air traffic in the next 20 years, while reducing airport arrival delay [11]. This estimation of future air traffic increment may be revised down due to COVID-19 impacts; however passenger and cargo movements are in large demand on a long-term basis.

Several studies have analyzed the aircraft arrival process at airports through queuing theory. Review of the conventional studies are summarized in [12]–[14]. Mostly, these studies do not make use of operational data or compare their results against actual data. On the other hand, authors have been proposed data-driven queuing approach using actual flight plans and aircraft track data [12]–[16]. Two types of distance-based queuing models, which enable us to present aircraft arrival processes by the distance at the destination airport, were proposed using arrival operational data at Tokyo International Airport. One of the models was applied to present arrivals at Singapore Changi International Airport, and the state of the arts results was briefly summarized in [16]. In the same line, this paper introduces distance-based queuing models which present aircraft arrival processes at Tokyo International Airport and Changi International Airport, and discusses efficient control strategies, which mitigate traffic congestion while reducing delay time, by comparing different features of the arrival traffic flow.

This paper is organized as follows. Section II introduces distance-based queuing models which present arrival traffic at an airport. Section III conducts data-driven analysis and determines stochastic parameters in the models. Section IV suggests efficient arrival strategies for minimizing traffic con-

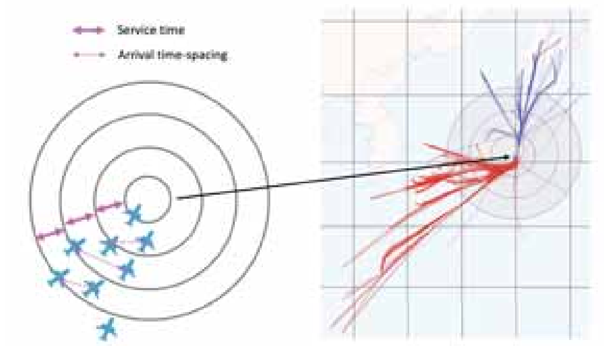


Figure 1. Illustration of the service time and inter-arrival time-spacing.

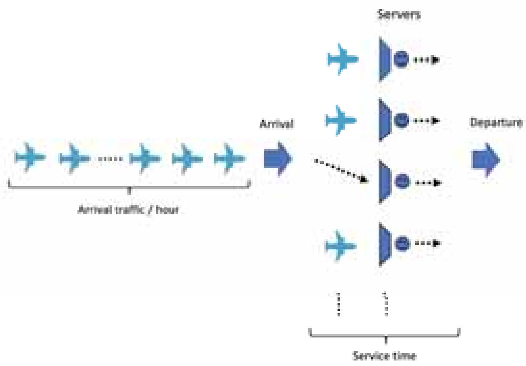


Figure 2. Example of a queuing model for aircraft arrival traffic.

gestion and arrival delay time at Tokyo International Airport. Section V analyzes the bottlenecks of arrival traffic flow at Changi International Airport through the distance-based queuing approach. Section VI concludes this paper and summarizes our future works.

II. Distance-based queuing model

A. Characteristics of aircraft arrival traffic

Conventional studies indicated that characteristics of the arrival traffic processes depend on the distance and/or flight time at the destination airport. In [9], the arrival process was classified by four distance-based stages. The first stage, where is the closest arrival stage at the destination airport, is the airspace which fully deterministic and time-based spacing is given to arrival traffic. It locates approximately 50NM away from the airport. The second stage is the transition between time-based and flow-based arrival traffic control. The third stage is the flow-based control stage, where metering is given to the arrivals to maintain safety and capacity at the airspace and runway at the destination airport. The fourth stage applies stochastic methods to estimate where and when pop-up flights are merged.

As a case study, characteristics of arrival traffic flows at Tokyo International Airport were analyzed based on distance-based queuing models [12]–[14]. An airspace area of radius 300NM around the airport was partitioned using concentric circles (see Fig. 1) centered at the airport, with radii at increments of 10NM. This partitioning defines 29 airspace areas $i = 1, 2, ..., 29$, where airspace $i = 1$ is the area around the airport in the circular ring defined by the 10 and 20NM radii, airspace $i = 2$ is the area around the airport in the circular ring defined by the 20 and 30NM radii, and so on.

B. Parameter settings

As shown in Fig. 1, arrival traffic at Tokyo International Airport (in year 2016 and 2017) mainly distinguished by two flows; one is arriving from south-west region, the other from north region. We focused on analyzing the traffic flow arriving from the south-west region at Tokyo International Airport, which is three times congested traffic comparing with the arrival traffic flow from the north.

Using the partitioned airspace $i \in \{1, 2, \dots, 29\}$, the time between two consecutive arrivals entering the airspace i (crossing the bigger concentric circle) is called the aircraft inter-arrival time. Upon arrival, the aircraft receive a service time at airspace i, which is the time the aircraft spends flying the airspace i. In this way, the distance-based arrival process is considered as a multi-server queuing model, in which the number of servers indicates the number of aircraft that are allowed to be present at any time in the given airspace i, which means the capacity of the airspace i. Fig. 2 explains the formulation of the queuing model at each airspace i. Each specific airspace is analyzed independently.

III. Data-driven analysis

A. Data statistics

First of all, statistical and stochastic features of aircraft arrival data were analyzed using flight plans and track data for 71 days selected from odd months of 2016 and 2017. All data cover nominal operation at Tokyo International Airport excluding weather impacts and other rare events [12]. In 2016, there were a total of 608 arrivals per day on average with 530 domestic and 78 international flights. In 2017 there were a total of 614 arrivals per day on average with 530 domestic and 84 international flights.

Total number of arrivals between 8:00 and 23:00 is slightly below the maximum allowed daily traffic thresholds, with the most congested period occurring between 17:00 and 22:00. Air traffic flow in Japan is controlled, with a central focus

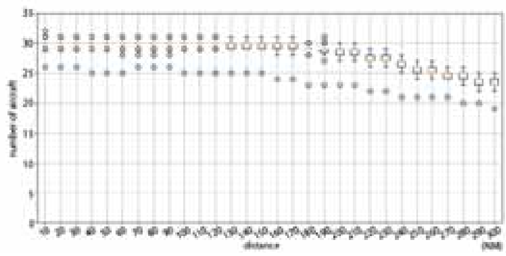
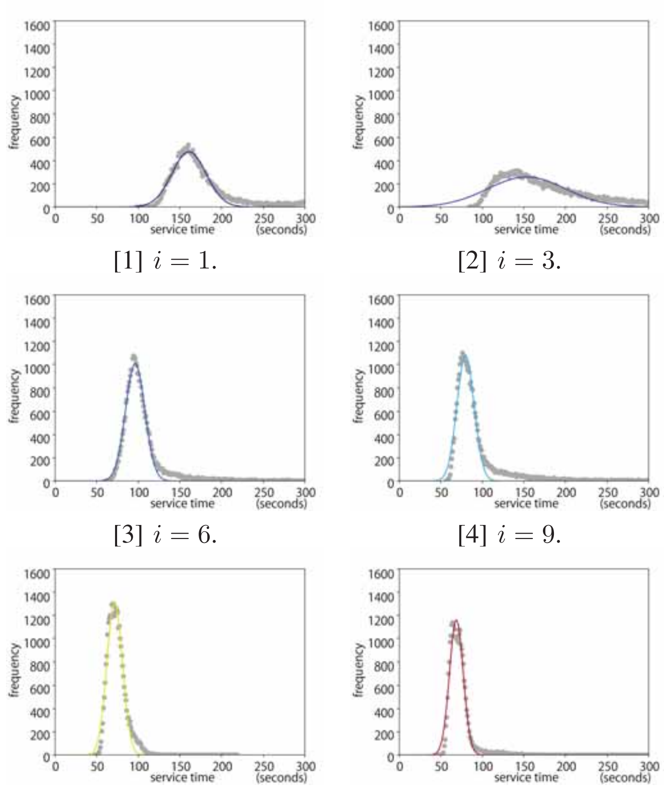
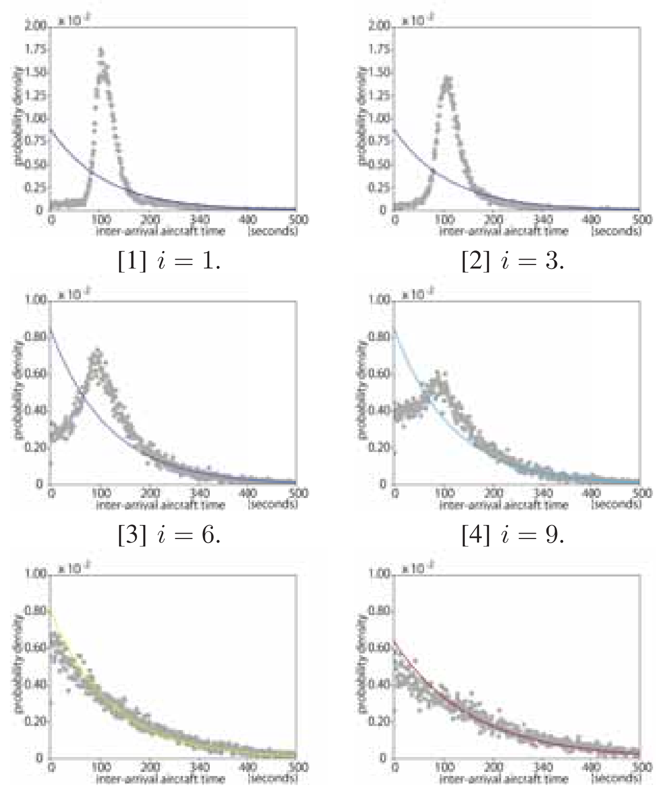


Figure 3. Arrival rate from south-west region at each concentric circles. [12]



[1] $i = 1$. [2] $i = 3$.
[3] $i = 6$. [4] $i = 9$.
[5] $i = 19$. [6] $i = 29$.

Figure 4. Distribution of service times with Gaussian fitting. [12]



[1] $i = 1$. [2] $i = 3$.
[3] $i = 6$. [4] $i = 9$.
[5] $i = 19$. [6] $i = 29$.

Figure 6. Distribution of inter-arrival times with exponential fitting. [12]

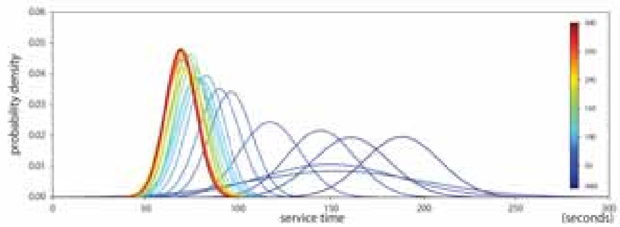


Figure 5. Comparison of characteristics of the service time via Gaussian distribution. [12]

on arrivals at Tokyo International Airport. Fig. 3 shows the average number of arrival flights from south-west region crossing every concentric circle (the x axis is radii of the concentric circles shown in Fig. 1) each hour between 17:00 and 22:00 for all the days. The total number of arrivals kept to maximum 40, including 30 from south-west and 10 from the north. The arrivals from south-west normally arrive at a runway only used for arrival traffic during peak periods.

B. Service time

Fig. 4 shows the empirical distribution of service times corresponding to the airspace $i \in \{1, 3, 6, 9, 19, 29\}$ with Gaussian fitting. As shown in Fig. 4, a Gaussian distribution approximates well the service time distribution. Fig. 5 compares the characteristics of the empirical service time distribution corresponding to airspace $i \in \{1, 2, \ldots, 29\}$ using Gaussian fitted distributions. These comparison of the service time at each airspace i emphasizes the strategies that the air traffic controllers use for arrivals at Tokyo International Airport. One of the most significant strategies is illustrated in the service time distribution for the airspace $i = 3$ and $i = 4$, which, together, correspond to the airspace between the concentric circles of radii 30 and 50NM. Fig. 5 shows that the service time variance is enhanced in these airspace areas compared to the other areas. This is explained by the fact that the arrival time-spacing is actively conducted by air traffic controllers in the airspace between the concentric circles of radii 30 and 50NM, just before the aircraft enter the terminal area.

C. Inter-arrival time

Fig. 6 shows empirical probability densities of aircraft inter-arrival time corresponding to the airspace $i \in \{1, 3, 6, 9, 19, 29\}$ with their exponential fittings. As shown in Fig. 6, data-driven analysis clarified that the empirical distribution of the inter-arrival time is well approximated by an exponential distribution where the arriving aircraft fly beyond the 150NM circle in a case study at Tokyo International Airport [12]. However, the inter-arrival times converge to a nearly Gaussian distribution towards the departure airports.

Based on the stochastic characteristics of Inter-arrival time and service time, we model the aircraft arrival process in an airspace using $G/G/c$ models in [12] [13], and a $M/G/c/K$

model in [14]. In this paper, a $G/G/c$ queuing model is briefly described in the next section. The $G/G/c$ queuing model allows general distribution for both service time and inter-aircraft time, thus well-present stochastic features of aircraft arrival process above.

IV. Analyzing arrival strategies at Tokyo International Airport

A. Model description

Here we apply a multi-server queuing model to each disjoint airspace areas $i \in \{1, 2, \ldots, 29\}$. Then, the aircraft arrival process can be formulated through a $G/G/c$ queuing model [12], [13].

Let D_i denote the delay an aircraft experiences in airspace area i. Then we approximate the total airborne delay in airspace area i as follows:

$$\mathbb{E}[D_i^{G/G/c}] \simeq \mathbb{E}[D_i^{M/M/c}] \frac{C_{A_i}^2 + C_{B_i}^2}{2}, \quad (1)$$

where $C_{A_i} = \frac{\sigma[A_i]}{\mathbb{E}[A_i]}$ is the coefficient of variation of the aircraft inter-arrival time in airspace area i and $C_{B_i} = \frac{\sigma[B_i]}{\mathbb{E}[B_i]}$ is the coefficient of variation of the aircraft service time in airspace area i. Here $\mathbb{E}[A_i]$ and $\sigma[A_i]$ are the mean and standard deviation of aircraft inter-arrival time, and $\mathbb{E}[B_i]$ and $\sigma[B_i]$ are the mean and standard deviation of aircraft service time in the airspace area i.

In Eq. (1), $\mathbb{E}[D_i^{M/M/c}]$ denotes the expected aircraft delay time in airspace area i when a $M/M/c$ queuing model is considered, which is well known [17], [18]. This means that the arrival process is considered as a Poisson process with a parameter λ_i, with service times are assumed to follow an exponential distribution with a parameter μ_i and there is a fixed number of parallel servers c_i.

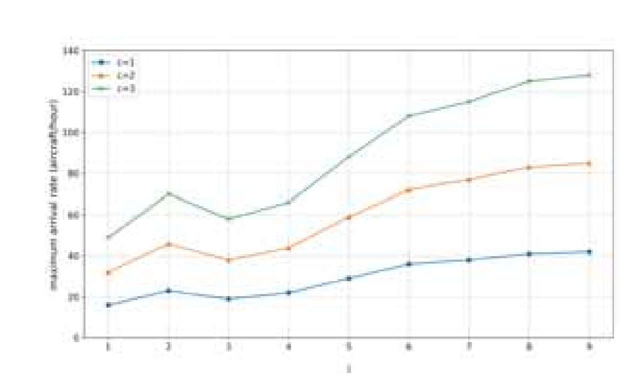


Figure 7. Comparison of maximum arrival rate . [14]

TABLE I. Minimum c_i values. [14]

Arrival rate	Airspace i								
(aircraft / hour)	1	2	3	4	5	6	7	8	9
30	2	2	2	2	2	1	1	1	1
35	3	2	2	2	2	1	1	1	1
40	3	2	3	2	2	2	2	1	1

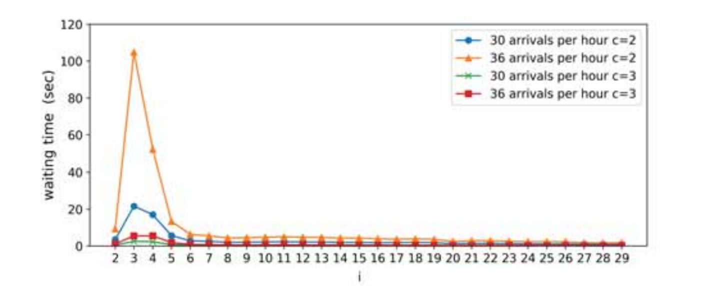


Figure 8. Expected arrival delay time at airspace i. [12]

Moreover, for stability, we have

$$\rho_i = \frac{\lambda_i}{c_i \cdot \mu_i} < 1. \quad (2)$$

If ρ_i is not lower than 1, then the queue becomes unstable and the estimated delay time for incoming aircraft tends to become extraordinarily long.

B. Bottlenecks in the arrival flow

First of all, the maximum arrival rate λ_i, which satisfies the stability conditions (see Eq. (2)) at each airspace i, was estimated under a fixed service rate μ_i, estimated using actual data, and airspace capacity $c_i \in \{1, 2, 3\}$, such that $\rho \to 1$. Fig. 7 shows the estimated arrival rate in an hour at airspace $i \in \{1, 2, \ldots, 9\}$. As shown in Fig. 7, increasing the airspace capacity c_i allows for higher arrival rates for all airspace i. For $c = 1$, 30 arrivals per hour is not allowed because the queue stability condition for airspace $i \in \{1, 2, \ldots, 5\}$ no longer hold. When $c = 2$, the maximum arrival rate allowed in airspace $i = 1$ is 32 arrivals, while 40 arrivals are not allowed in airspace $i = 3$. If $c = 3$, it is possible to have 40 arrivals per hour for all airspace.

Tab. I summarizes the minimum c_i values to stabilize the $G/G/c$ model for airspace $i \in \{1, 2, \ldots, 9\}$. This shows that the airspace closer to the airport requires more capacity (large values for c_i), especially in the airspace $i \in \{1, 3\}$. This is because close to the destination airport, i.e. airspace $i = 1$, the aircraft slow down. Thus, the mean service rate is reduced. In the airspace $i = 3$ and 4, especially $i = 3$, the inter-arrival time is controlled by using vectoring operations. As a result, in this airspace the aircraft change their heading direction and adjust the spacing between succeeding aircraft. Therefore, the service rate μ_i is reduced in the airspace $i = 1, 3, 4$. In $i = 2$, the aircraft inter-arrival time is already controlled, and most arriving aircraft follow in-trail because the airspeed is faster than in the $i = 1$ airspace.

C. Arrival strategies for optimizing future arrival flows

Fig. 8 compares waiting time (arrival delay time) estimated by Eq. (1) for airspace $i \in \{2, 3, \ldots, 29\}$ in four cases; (1) 30 arrivals per hour when $c = 2$, (2) 36 arrivals per hour when $c = 2$, (3) 30 arrivals per hour when $c = 3$, (4) 36 arrivals per hour when $c = 3$. Increasing future arrivals by 20 % was given as 36 arrivals per hour. When $i = 1$, the $G/G/c$ queue

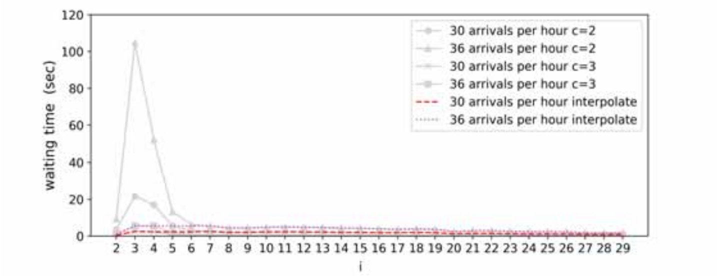


Figure 9. Interpolating the plot of arrival delay time between $c = 2$ and $c = 3$ at airspace i. [12]

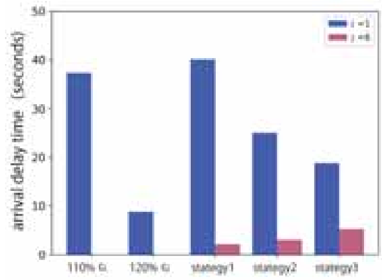


Figure 10. Comparing arrival strategies.

TABLE II. Arrival strategies by adjusting mean of service time $\mathbb{E}[B_i]$ at further airspace from the destination airport.

Airspace area j	1 (20-150NM)	2 (150-300NM)
Strategy 1	$\mathbb{E}[B_1] - 100$ sec	$\mathbb{E}[B_2] + 100$ sec
Strategy 2	$\mathbb{E}[B_1] - 150$ sec	$\mathbb{E}[B_2] + 150$ sec
Strategy 3	$\mathbb{E}[B_1] - 180$ sec	$\mathbb{E}[B_2] + 180$ sec

was not stable ($\rho > 1$, see Eq. (2)) when assuming 36 arrivals with $c = 2$, so airspace $i = 1$ was not considered in Fig. 8 for the comparison with other airspace.

As shown in Fig. 8, arrival delay time increases at airspace $i = 3$ and 4 when assuming current capacity $c = 2$; currently (30 arrivals per hour) maximum 22 seconds, and increasing to 105 seconds when assuming 20 % increase of arrival rate (36 arrivals per hour). However, increasing airspace capacity to $c = 3$ reduces arrival delay time at both airspace $i = 3$ and 4. These results show that decreasing the minimum aircraft separation has a positive impact not only by increasing runway throughput, but also by decreasing arrival delay times in the key airspace areas. For this purpose, the effectiveness of introducing new wake vortex category, RECAT (Re-categorization of wake turbulence categories), was discussed in [12], [13]. Fig. 9 shows that the most efficient transition $c = 2$ to $c = 3$ will be realized around 70NM distance from the airport.

One other means to limit the arrival delay time is to reduce the service time $\mathbb{E}[B_i]$, which is equivalent to reducing the flight time of the aircraft in busy airspace. Conventionally, it was proposed that extending flight time in en-route airspace located farther away from the destination airport than the terminal airspace surrounding the airport [1]. In the same line, the impact of arrival time adjustments in the en-route

Figure 11. One day examples of flight track data arriving at Singapore Changi International Airport within 500 NM radii concentric circle centered at the airport.

Figure 12. One day examples of arrival tracks around Singapore Changi International Airport, emphasizing holding areas.

airspace was compared with the strategy to increasing airspace capacity close to the destination airspace [13]. Tab. II shows three strategies at airspace $j \in \{1, 2\}$; airspace $j = 1$ is the area around the airport in circular ring defined by the 20NM and 150NM radii, and airspace $j = 1$ is the area in circular ring defined by 150NM and 300NM radii centered at Tokyo International Airport. For Strategy 1, we reduce the mean of service time $\mathbb{E}[B_j]$ by 100 seconds at airspace $j = 1$, and increase $\mathbb{E}[B_j]$ by 100 seconds at airspace $j = 2$. Simultaneously, we shift 150 seconds and 180 seconds from airspace $j = 1$ to $j = 2$.

Fig. 10 compares arrival delay time at airspace $j \in \{1, 2\}$ using $M/G/c/K$ queuing model [13]. In Fig. 10, we also consider two more strategies; increasing airspace capacity by 10% ("110% c_j") and by 20% ("120% c_j"). The results show that Strategies 1, 2, and 3 successfully transfer the arrival delay time from the airspace $j = 1$ to $j = 2$. However,

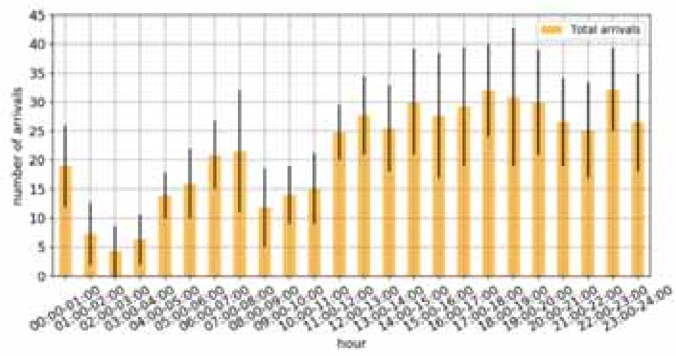
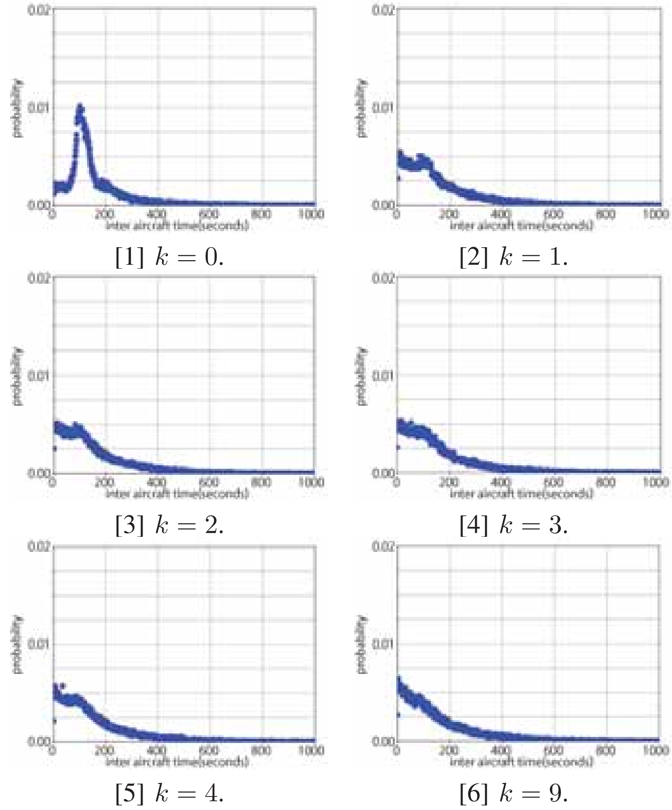


Figure 13. Arrival rate at Changi International Airport at each time period.

Figure 14. Distribution of the departure airports of the arrivals at Changi International Airport.



[1] $k = 0$. [2] $k = 1$.
[3] $k = 2$. [4] $k = 3$.
[5] $k = 4$. [6] $k = 9$.

Figure 15. Distribution of inter-arrival times.

the most effective strategy to minimize the arrival delay is to increase the airspace capacity by 20% ($120\%c_j$ in Fig. 10). Although the optimizing service time in each airspace needs further analysis, these results contribute to prioritizing future strategies on improving air traffic management systems to limit arrival delay while allowing an increase in the air traffic volume.

In the next section, we apply one of the distance-based approach using $G/G/c$ queuing model to Singapore Changi International Airport, and analyze the bottleneck of aircraft arrival traffic.

V. Applying the proposed modeling to Singapore Changi International Airport

A. Data description

ADS-B data of flight tracks in 2019 (total 110 days from March to September) arriving at Singapore Changi Airport was used in the present study. ADS-B data cover most of the flights under instrument flight rules (IFR) and capture essential characteristics of incoming traffic flows [19]. Excluding day traffic under non-nominal operation (extremely small number of traffic in a day), arrival traffic data was interpolated every second and used in the analysis.

Fig. 11 shows an example one-day track data arriving at Changi International Airport within a 500NM radii concentric circle centered at the airport. Concentric circles every 10NM from 10NM to 300NM radii are drawn in the figure. Fig. 12 enlarges Fig. 11 and shows arrival track data close to the airport. As shown in Figs.11 and 12, omni-directional air traffic flows arrive at Changi airport, and spacing efforts, including holding and vectoring, are given to merge arrivals close to the airport approximately within 50NM airspace area.

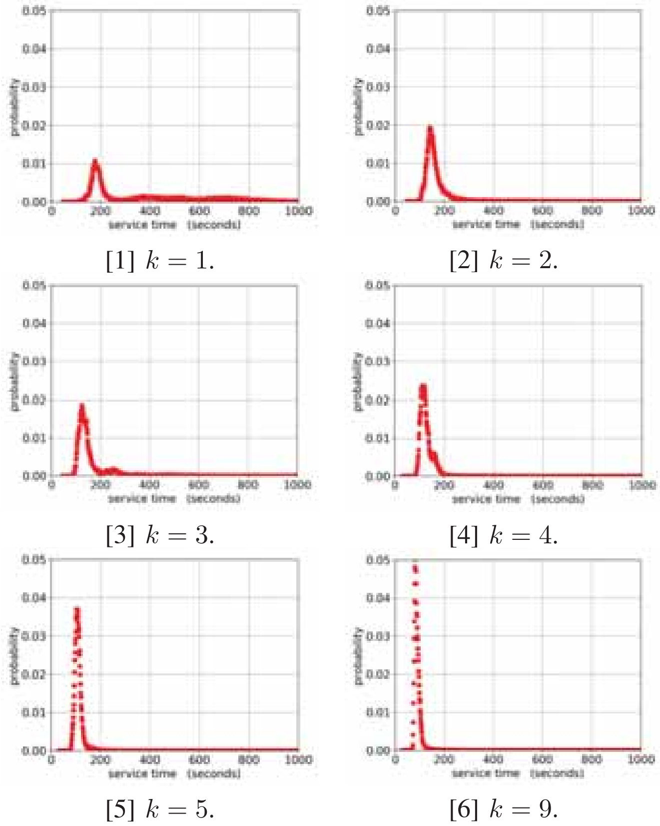
Fig. 13 shows arrival rate per each hour in a day by mean (bar) and standard deviation (black whisker) of the ADS-B data. The total number of arrivals between 0:00 and 10:00AM is below the maximum rate in a day, with the most congested period occurring between 10:00AM and 24:00.

Fig. 14 shows distributions of departure airports of arrivals at Changi International Airport. International flights arrive at the airport from all over the world, and the flights from the ASEAN region hold the largest share.

B. Stochastic features

Using the ADS-B track data, aircraft arrival process at Changi International airport is modeled applying the distance-based queuing model. The airspace within 100NM radii concentric circle centered at the airport is partitioned by 10 areas, airspace $k \in \{0, 1, 2, \ldots, 9\}$; airspace $k = 0$ is the area within 10NM radii circle, airspace $k = 1$ is the area around the airport in the circular ring defined by the 10 and 20NM radii, and so on.

Fig. 15 compares probability distribution of inter-aircraft time entering each airspace $k \in \{0, 1, 2, 3, 4, 9\}$. Variances of the inter-aircraft time grows more than the actual ones because the ADS-B data does not cover 100% of the arrival traffic due to ADS-B's surveillance limitation. Although these data limitation causes larger variance than the actual traffic, the peak in the distribution is disappeared at farther airspace than



[1] $k=1$. [2] $k=2$. [3] $k=3$. [4] $k=4$. [5] $k=5$. [6] $k=9$.

Figure 16. Distribution of service times.

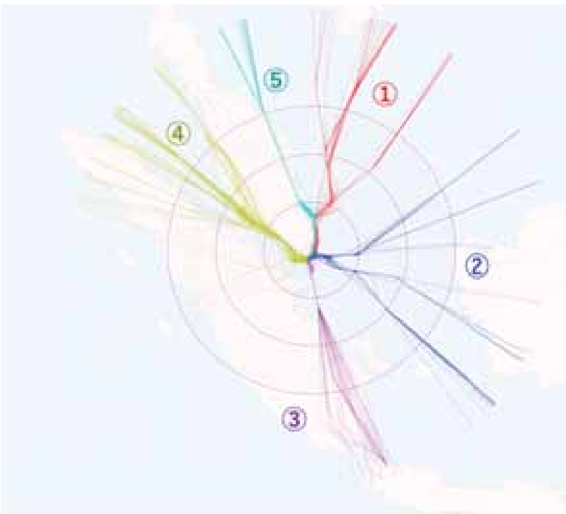
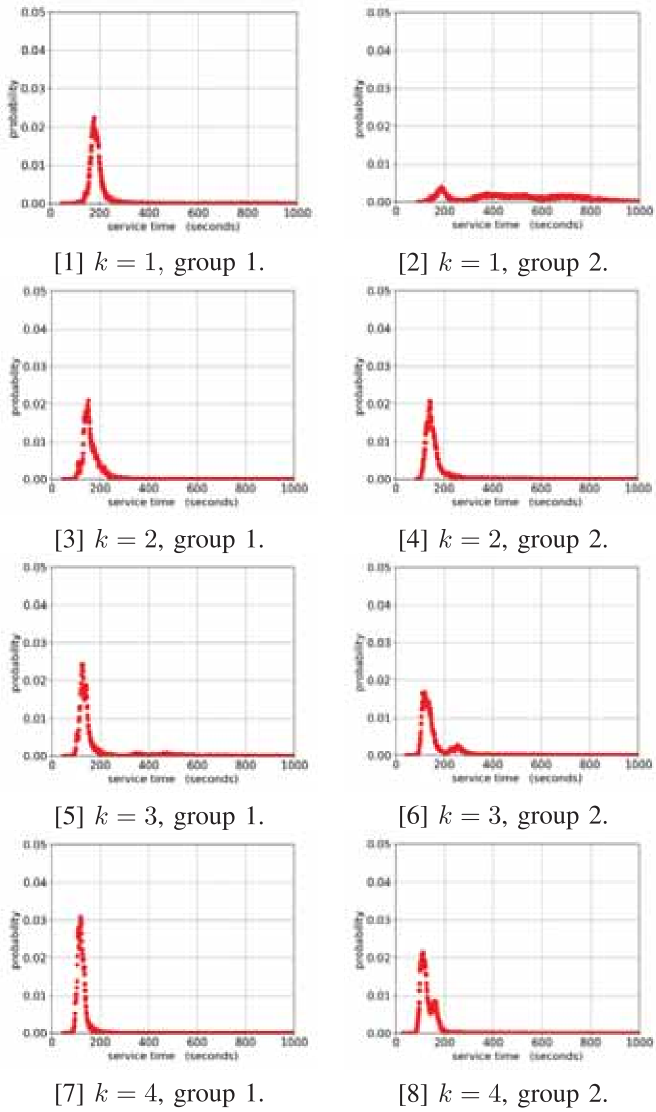


Figure 17. One day examples of arrival track data with five clusters.



[1] $k=1$, group 1. [2] $k=1$, group 2. [3] $k=2$, group 1. [4] $k=2$, group 2. [5] $k=3$, group 1. [6] $k=3$, group 2. [7] $k=4$, group 1. [8] $k=4$, group 2.

Figure 18. Distribution of service times for each group.

$k=1$. This indicates that the arrival spacing is controlled very close to the airport approximately around 10NM distance from the airport.

Fig. 16 shows probability distributions of service time at airspace $k \in \{1,2,3,4,5,9\}$. The variance in the distribution grows at the airspace closer to the airport. This shows that the air traffic controller adjust flight time more at the airspace close to the airport.

To analyze arrival strategies depending on the arrival traffic flows, we categorize the flow by five clusters as shown in Fig. 17. The first and fifth clusters in Fig. 17 are merged in en-route airspace, so they are defined as the same traffic group (group 1). The second, third, and forth clusters are defined as group 2. Then, probability densities of service time at airspace $k \in \{1,2,3,4\}$ are compared in Fig. 18. As depicted in Fig. 18, the mean and variance of the service time in group 2 at $k=1$ grows. These are the effect of route designs and arrival operation, which merges arrival traffic at airspace $k=1$ right before the approach routes. At airspace $k=3$ and 4, small peaks appears to increase service time. As shown in Fig. 12, flight time is controlled by holding at these airspaces for group 2 arrivals.

C. Bottlenecks in the current arrival flows

As shown in the previous section, group 2 arrival traffic impacts on increasing service time (flight time) $\mathbb{E}[B_k]$at airspace

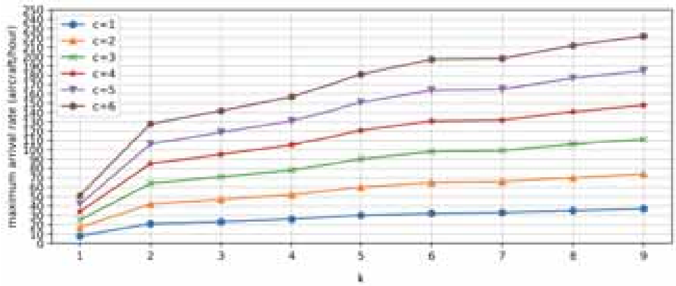


Figure 19. Comparison of maximum arrival rate.

TABLE III. MINIMUM c_k VALUES.

Arrival rate	Airspace k								
(aircraft / hour)	1	2	3	4	5	6	7	8	9
30	4	2	2	2	1	1	1	1	1
35	5	2	2	2	2	2	2	1	1
40	5	2	3	2	2	2	2	2	2

$k = 1$. Reducing service rate $\mu_k = 1/\mathbb{E}[B_k]$ increases ρ_k, which is a key parameter that impacts on the $G/G/c$ queuing model as shown in Eq. (2).

Fig. 19 compares the maximum arrival rate which satisfies the stability condition shown in Eq. (2), when $c = 1, 2, 3, 4, 5, 6$ are given at airspace $k \in \{1, 2, \ldots, 9\}$. In all given c values, the maximum arrival rate at airspace $k = 1$ is limited comparing with the other airspace. For stabilizing the queuing system at airspace $k = 1$, $c > 4$ is required when 30 aircraft arrives in an hour, and $c > 5$ when 40 arrivals in an hour. This means that the current arrival strategy at $k = 1$ airspace requires higher airspace capacity right before approach phase during congested periods.

Tab. III summarizes minimum capacity value c_k, which satisfies Eq. (2). As shown in Tab. III, airspace closer to the airport requires more capacity, especially at airspace $k = 1$. Comparing with the minimum capacity values c_i in Tab. I for arrivals at Tokyo International Airport, it is obvious that different arrival strategies are given to these case study airports.

VI. CONCLUDING REMARKS

This paper introduced distance-based queuing models and discussed control strategies in aircraft arrival operation. Two case study airports, Tokyo International Airport and Changi International Airport, were selected, and a large volume of flight plans and track data set was used in stochastic and statistical analysis. These data-driven analysis enable to estimate current and future arrival strategies and suggest even better arrival strategies which mitigates traffic congestion while reducing arrival delay time at the destination airport.

In the future work, we further analyze arrival strategies at Tokyo and Changi International Airport. Comparing arrival strategies at different features in traffic flows and environments contributes to establish systematic approaches for designing flow-based and time-based air traffic management on the ground. The outcomes of this study provide insights into the effectiveness of arrival control strategies and are seen as a means to recommend scenarios to be further analyzed not only with fast-time and numerical simulations, but also with human-in-the-loop simulations which air traffic controllers participate.

ACKNOWLEDGMENT

This research was supported by JSPS KAKENHI Grant Number 20H04237, Japan Civil Aviation Bureau (JCAB) and the Civil Aviation Authority of Singapore. The authors are grateful to JCAB for providing air traffic data and to Ms. Mayumi Ohnuki for assisting data preparation and figure corrections. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors.

REFERENCES

[1] H. Erzberger and E. Itoh, ”Design Principles and Algorithms for Air Traffic Arrival Scheduling”, NASA/TP-2014-218302, 2014.

[2] Federal Aviation Administration (FAA), ”NextGen Portfolio - Time-based Flow Management”, 2017.

[3] J. Thipphavong, J. Jaewoo, H. Swenson, L. Martin, M. Lin and J. Nguyen, ”Evaluation of the terminal sequencing and spacing system for performance-based navigation arrivals”, IEEE/AIAA 32nd Digital Avionics Systems Conference (DASC), 2013

[4] P. Van Tulder, ”Flight Deck Interval Management Flight Test Final Report”, NASA/CR-2017-219626, 2017.

[5] M. Schultz, H. Fricke, T. Kunze, J. Mund, J. López. Leonés, C. Grabow, J. De. Prins, M. Wimmer, and P. Kappertz, ”Uncertainty handling and trajectory synchronization for the automated arrival management”, 2nd Eurocontrol SESAR Innovation Days, 2012.

[6] European Commission, ”Cross Border SESAR Trials for Enhanced Arrival Management: Periodic Reporting for period 1 - PJ25 XSTREAM”, 2017.

[7] International Civil Aviation Organization, ”Long range ATFM concept trials”, The 8th Meeting of the ICAO Asia/Pacific Air Traffic Flow Management Steering Group (ATFMSG/8), 2018.

[8] E. Itoh, M. Brown, A. Senoguchi, N. Wickramasinghe, and S. Fukushima, ”Future arrival management collaborating with trajectory-based operations”, Air Traffic Management and Systems II, Springer, pp.137-156, 2017.

[9] E. Itoh, Y. Miyazawa, M. Finke, J. Rataj, ”Macroscopic Analysis to Identify Stage Boundaries in Multi-Stage Arrival Management ”, Air Traffic Management and Systems IV, Springer nature, 2020 (in press).

[10] D. Arbuckle, ”Interval Management Application”, ICAO Aircraft Surveillance Applications Workshop, March 2017.

[11] International Civil Aviation Organization, ”Long-Term Traffic Forecasts Passenger and Cargo”, 2016

[12] E. Itoh and M. Mitici, ”Queue-based Modeling of the Aircraft Arrival Process at a Single Airport”, Aerospace, 6, 103, 2019.

[13] E. Itoh and M. Mitici, “Analyzing Tactical Control Strategies for Aircraft Arrivals at an Airport Using a queuing Model”, Journal of Air Transport Management, Volume 89, 101938, 2020 .

[14] E. Itoh and M. Mitici, “Evaluating the Impact of New Aircraft Separation Minima on Available Airspace Capacity and Arrival Time Delay”, The Aeronautical Journal, Volume 124, Issue 1274, pp.447-471, 2020.

[15] E. Itoh and T. Otsuyama, ”Status of Interval Management (IM) related research activities in Japan”, ICAO Information paper, SP-AIRB WG/9-IP/02, April 2020.

[16] E. Itoh, M. Schultz, S. Athota, and V. Duong, ”Ground-based Interval Management Related International Collaborative Research Targeting Arrivals at Singapore Changi International Airport”, ICAO Information paper, SP-AIRB WG/10-IP/01, 2020.

[17] I. Adan and J. Resing, ”Queuing Systems”, 2015.

[18] F. Hillier, ”Introduction to Operations Research”, Tata McGraw-Hill Education, 2012.

[19] M. Schultz, X. Olive, J. Rosenow, H. Fricke, and S. Alam, ”Analysis of airport ground operations based on ADS-B data”, 1st International Conference on Artificial Intelligence and Data Analytics for Air Transportation, 2020.