

Macroscopic Analysis to Identify Stage Boundaries in Multi-stage Arrival Management



E. Itoh, Y. Miyazawa, M. Finke, and J. Rataj

Abstract Accommodating the air traffic growth, reducing arrival delay is one of the most important functions of designing the ATM system. One of the newest concepts to further optimize arrival flows is multi-stage arrival management, proposed by DLR, in which different guidance principles to manage the arriving traffic are implemented in different stages. These stages are optimized to the core management task to be done in a certain area of the arrival stream and the conditions of the surrounding environment. This paper discusses this concept through a macroscopic analysis on the overall arrival traffic flows. Further, this paper analyzes parts of the multi-stage arrival management concept applied to Tokyo International Airport as a case study. A stochastic characteristic of arrival trajectories will be discussed as a counterpart of conventional deterministic trajectory-based operation based on data-driven analysis and arrival procedures at the airport. The best strategies of shifting arrival flow control to time-based management are analyzed based on the stochastic data analysis. Impacts of pop-up aircraft are discussed as one of the causes to increase uncertainties in aircraft trajectory management.

Keywords Arrival management · Multi-stage · Arrival delay · Air traffic management

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1 Introduction

Highly frequented airports are the critical elements in air traffic. In the most cases, they are directly or implicitly the origin of delays in the air traffic system. Therefore, arrival management is an essential part in air traffic management. To clarify the meaning of arrival management, the following definition from EUROCONTROL [1] is used: “Arrival management is a general term given to the process of safely and effectively arranging arrivals into a smooth efficient flow for landing at a destination airport.” To improve the arrival management process, controllers (ATCo) are supported by a family of decision support systems called arrival managers (AMANs). According to [1], an AMAN is defined as a software specifically designed to provide assistance in metering and sequencing arrival streams and that delivers information needed to implement an efficient arrival management. Following this definition, the first AMANs were built already more than 20 years ago. The tasks, where the controller is usually supported by an AMAN, are:

- Build an arrival sequence.
- Assign an arrival time at the runway threshold and other significant waypoints for each aircraft in the sequence.
- Predict a trajectory for each aircraft which implements the assigned landing time.
- Transform the trajectory into appropriate guidance instructions which are transmitted to the pilot.

2 Drawbacks of Modern Arrival Management Systems

One drawback of current AMAN designs is the effect of model uncertainties in the trajectory calculation and the probability of disturbances. As a consequence, the individual trajectory reliability decreases considerably with increasing distance of the aircraft to the airport. Hence, the drawback of the extension of the current planning horizon from 80 NM by a factor of 5 is the decreasing predictability and accuracy of the calculated trajectory. Furthermore, horizons of 500 nautical miles and more causes that some aircraft in the approach flow are still on the ground, as they are departing from airports that are less than 500 nautical miles away from the destination. Because the uncertainties as well as the probability of disturbances for a flight on ground are much higher as it is the case for airborne flights, the predictability and the quality of the trajectory are even worse. Hence, without additional effort concerning the concept of operation and the used methods as well as the existing planning mechanisms, the new approach results in decreased prediction quality of arrival time, and increased number of arrival sequence changes with negative effects on the aircraft, ATC, and airport operation. Moreover, corrective measures for an individual aircraft far away from the airport may become useless due to unexpected new disturbances that again reduce efficiency.

The trajectory-based operational concept recently described by SESAR provides a 4D trajectory for each aircraft, the so-called business trajectory [5]. This trajectory is designed so that the flight can be managed as closely as possible to the airspace user's ideal profile. Besides the three spatial dimensions, the trajectory also contains the dimension "time." 4D trajectories for the arrival phase can be planned by arrival management systems with long lead times which are conflict free, with an optimized landing sequence [1]. Nevertheless, in a pure trajectory-based ATM, this logically requires that all flights follow exactly these planned trajectories also in reality to guarantee that they stay free of conflicts and to avoid any corrective actions by ATC. The constraint to stay on a preplanned trajectory results in an increased number of control actions for the aircraft due to uncertainties and disturbances, like wind effects. Negative consequences of increased control actions are again an increased fuel consumption and, more important, an increased maintenance effort for the engines as well as a low acceptance by the pilots due to their increased workload. Additionally, some disturbances might have such an impact that increased control actions alone cannot maintain the optimized and conflict-free trajectory situation, like suddenly occurring emergency flights treated with absolute priority.

The described drawbacks require the development of new concepts of operation, methods, and planning algorithms for AMANs, taking the drawbacks into account, which stem from uncertainties and disturbances. Different solutions for airborne arrivals and arrivals that are still on ground at their departure aerodrome are needed as the different status has a significant influence on the uncertainties as well as the probability of disturbances impacting a flight. Hence, using today's planning and guidance functionalities for arrival management is disadvantageous.

The future arrival management will further be strongly influenced by the introduction of new wake turbulence categories. In the past, a 3×3 matrix was used to define the separation distances between the subsequent aircraft. These aircraft categories are heavy, medium, and light, and the number of different separations in the 3×3 matrix is 3 (4, 5, 6 NM) [5]. In this case, the controllers are able to remember this low amount of numbers of different separation minima for the aircraft pairs; hence, no further support was required to apply them to the aircraft on final approach. With the introduction of RECAT-EU, as an example, the number of aircraft categories increases to 6 and the number of different separation values to 8 in a 6×6 matrix [6]. The new wake turbulence categories increase the complexity for the controller considerably. To deal with that the controller needs additional support tools to create an efficient arrival sequence. Further considerations go in the direction to assign every individual aircraft pair an individual separation [7]. To guide such a separation scheme, it is indispensable to intensively support the controller with technical means.

3 Concept of Multi-stage Arrival Management

Following the description in the previous chapters, it becomes apparent that more and more tasks of the arrival management are collected under an AMAN, which makes

these systems more and more complex. By extending the planning horizon considerably, arrival management starts much earlier than in the past. The implementation of new separation values requires new support elements in the AMAN close to the runway.

It can be concluded that the driving requirements rules to be followed and constraints to be considered in future arrival management will at least depend on

- the distance of the airplane to the destination aerodrome,
- the characteristics and local constraints of main arrival flows,
- the diversity of involved aircraft type performance and equipment,
- the flight phase,
- predictability of traffic as well as accuracy and uncertainty of planning systems.

Although the list of dependencies can surely be further extended, state-of-the-art AMANs are still using the same algorithms for the whole traffic up to the planning horizon while not or not sufficiently considering the items contained in the list above. In addition, especially trajectory-based deterministic calculations seem to be unsuitable without a minimum level of predictability and only tolerate minor uncertainties. A better solution could be to adapt and optimize the working principles of AMAN systems according to these dependencies taking into account system architecture considerations.

This would result in a “clustering” of coherent tasks, methods or procedures, following the “separation of concerns” software architecture principle [8]. Supplementary to “separation of concerns” is the “single responsibility principle” in the software engineering domain. Taking these software architecture principles into account, it is necessary to divide future AMANs with their various “concerns” in different modules.

This approach can be realized with a multi-stage AMAN design defined by DLR, where several different sub-systems can use different working principles on different flight phases, arrival flows, or distances from the destination aerodrome. This design allows using the working principle which fits best to the single stages and offers also a lot of optimization potential for the whole AMAN architecture at the individual airports (see Fig. 1).

At its current stage of development, the multi-stage AMAN concept includes the following types of stages already:

- classical 4D trajectory-based, fully deterministic stages,
- time-based stages
- flow-based stages
- stages using stochastic methods.

Further types of AMAN stages may be available in future.

In addition, inspired by electric circuit or space launcher construction principles, two different types of stage arrangements can be identified:

- serial arrangement, where one stage directly feeds the traffic into another stage,

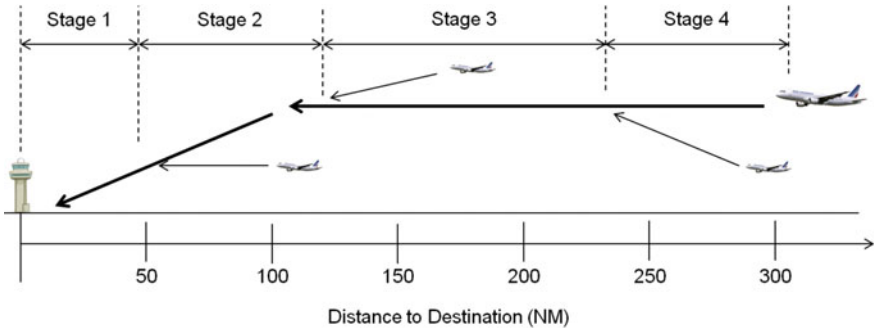


Fig. 1 Fictional example of a possible multi-stage AMAN design

- parallel arrangement, where separate airspaces, arrival flows, or otherwise, clustered arrivals are planned and handled by two stages in parallel.

Based on the description of the preceding chapters, a first stage/concern could be defined for the final approach area of an airport, where the main task is to create a tight sequence of aircraft on the center line by minimizing the used buffers on top of the minimum wake turbulence separation. At hub airports, this task is done by the so-called Director controller position which is very much specialized and focused just on this single task of creating the safe and effective sequence of aircraft on final track. Furthermore, the increasing task complexity by new wake turbulence categories and the focus on a time dependent separation between subsequent aircraft increases the distance of concerns to a trajectory-based approach.

A second stage/concern could be driven by trajectory-based operation with the goal to create an optimized aircraft sequence and feeding of the first stage defined above. Optimized aircraft sequence means that the order of the arriving aircraft corresponds to a previously defined optimization criterion. Furthermore, a high quality of the trajectory calculation is necessary to enable continuous descent approaches with engines in idle which are especially environment friendly. Here, it is important to start the calculation of the aircraft trajectory at least before the top of descent. In addition to sequencing, the trajectory-based approach enables a collision detection and avoidance in the TMA which is of utmost importance to ensure a safe and orderly traffic flow.

A third stage could be allocated to the arrival management of distant flights still in the en route phase of flight. Following the draw backs in chapter 2, another approach to guide the traffic should be taken into account here. This approach is based on statistical information which enables a continuous flow of aircraft to the airport without a high amount of corrective action. In contrast to this approach, precise trajectory-based operations would require a high amount of corrective actions of the aircraft as they have to follow their precisely planned but uncertain trajectories. More details concerning the statistical arrival management approach will be presented in a separate paper in the near future.

In order to build an AMAN system according to the multi-stage design, several decisions have to be made:

- type of the stage used for a defined part of the whole arrival management,
- serial or parallel arrangement of the individual stages,
- data exchange and transition conditions between the different stages,
- definite borders between the different stages/concerns.

A first scientific study has already been made by the Japanese research Electronic Navigation Research Institute (ENRI) on the definition of a possible border between flow-based and trajectory-based arrival management for Tokyo-Haneda International Airport, which is described in the following chapters.

4 Data-Driven Analysis

4.1 Case Study Data Description—Tokyo International Airport

Prior to discuss stage boundaries in the arrival management, this section introduces aircraft arrival operations at Tokyo International Airport, which this paper focuses on as a case study airport.

In total, maximum number of 447,000 departures and arrivals are accepted per year, with a maximum 80 operations in one hour. The airport makes use of four runways on daily basis, while the choice of the runway configuration depends on wind direction.

Over 60% of the domestic flights in Japan are concentrated at this airport. Figure 2 shows the distribution of departure airports with average number of departure aircraft arriving at Tokyo International Airport in Japan.

4.2 Stochastic Analysis on Air Traffic Arrival Flow

In order to characterize arrival traffic flow in each stage (see Fig. 1), a data-driven analysis is conducted using two years of radar tracks and flight plans in 2016 and 2017. Figure 3 shows definitions of aircraft flight time and inter-arrival time using concentric circles centered at Tokyo International Airport. In total, 29 datasets of aircraft flight time and inter-arrival time are defined when using a maximum radius of 300 NM with an increment of 10 NM. Aircraft inter-arrival time is defined as aircraft time-spacing between preceding and succeeding aircraft at each concentric circle. For example, the first dataset is difference of aircraft's crossing time after its proceeding aircraft crossed at the circle with 20 NM radius, the second dataset is the time difference at the circle with 30 NM radius, and so on.

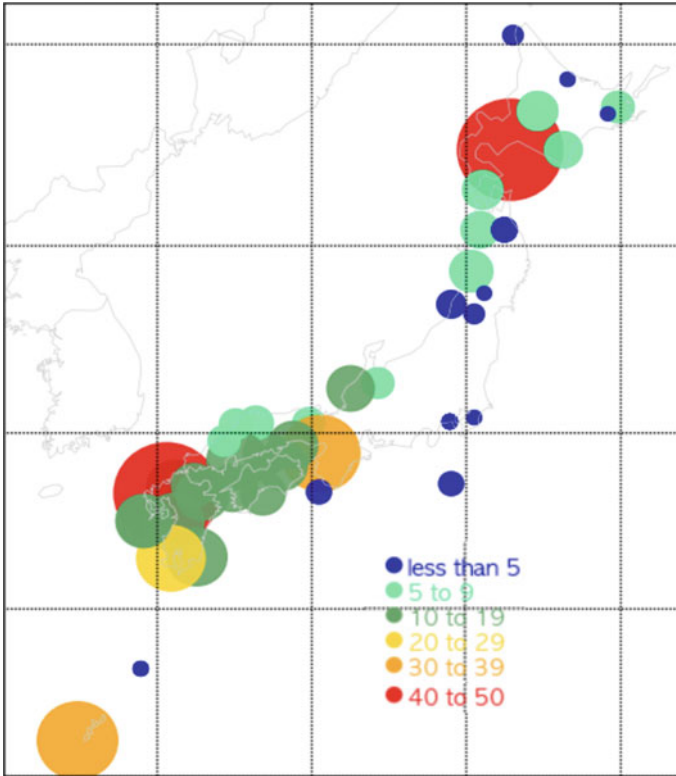


Fig. 2 Distributions of departure airports with average number of departures arriving at Tokyo International Airport in a day

Authors' past works indicated that the empirical distributions of the aircraft flight time could be numerically approximated using Gaussian distribution [9, 10]. The significant features of arrival traffic control appeared in the variances of the aircraft flight time distributions. Figure 4 compares flight time distributions corresponding to the arrival traffic flows from southwest direction. One of the most significant arrival strategies is illustrated in Fig. 4 for airspace between concentric circles 30 and 40 NM, 40 and 50 NM radii, where the variances grow dramatically in the arrival traffic flows from southwest direction. This explained by the fact that the arrival time-spacing was actively conducted by the air traffic controllers in the airspace between 30 and 50 NM away from the airport, just before the aircraft enter the terminal area. The increase in both the mean flight time and the flight time variance in the direction of the airport is due to the airspeed reduction that arriving aircraft undertakes prior to landing. For flight time, the mean and variance converge close to the circle of radius 200 NM. This circle captures current arrival strategies, since this is the airspace within which the traffic control capacity is met, and the spacing at merging points is filled. Between circles of radii 200 and 300 NM, air traffic controllers make an effort to maintain

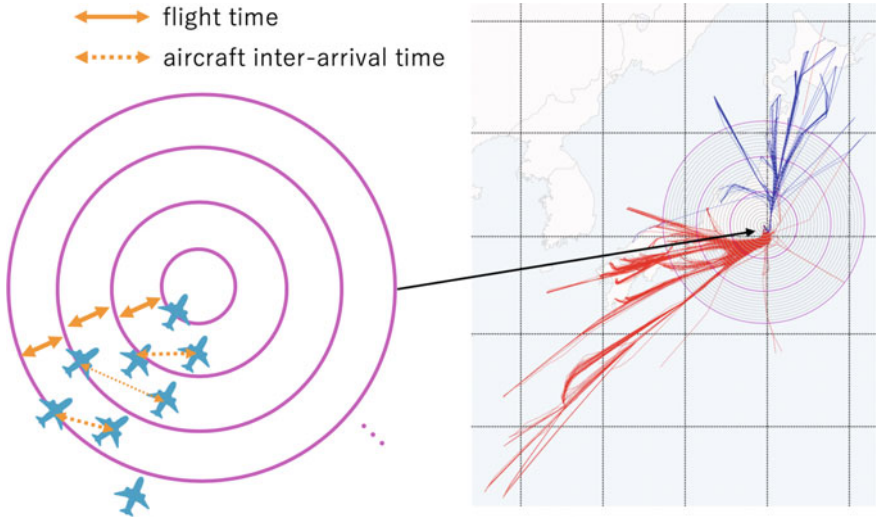


Fig. 3 Definitions of flight time and aircraft inter-arrival time in this paper. Map of Japan is drawn with flight tracks during an entire day in November 2016 [9]. The red tracks show the southwest traffic flow. The blue tracks show the north traffic flow.

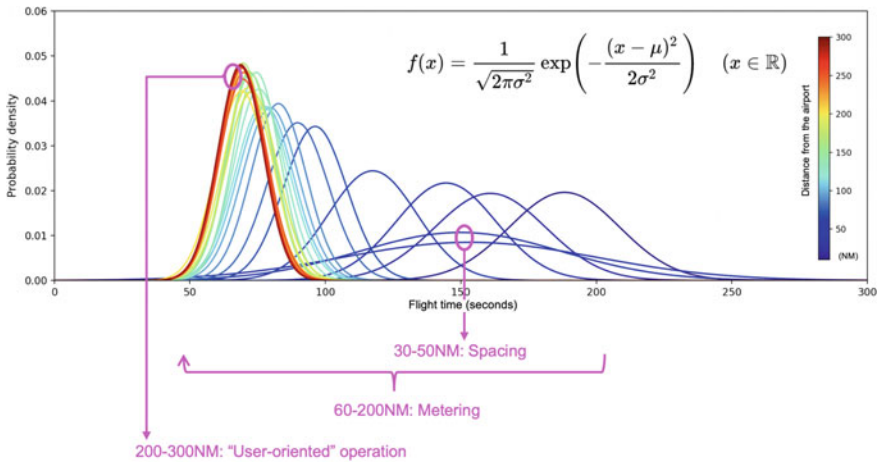


Fig. 4 Comparing flight time distributions every 10 NM radius, 10–300 NM

safe and efficient traffic flows by prioritizing airlines’ own procedures. In summary, there are three main strategies illustrated in Fig. 4: (1) arrival time-spacing within the circle around 50 NM, especially between the 30 and 40 NM radii circles; (2) arrival metering for traffic capacity control and spacing at merging points between the 50 and 200 NM circles; and (3) maintaining efficient traffic flow by prioritizing

airlines' own procedures beyond the 200 NM circle. Minimizing arrival delays and operational costs requires great consideration in combining these different strategies.

Figure 5 compares exponential fittings and empirical probability densities of the aircraft inter-arrival time from the southwest direction at concentric circles with 50, 100, 150, and 300 NM radii [10]. The empirical distribution of the inter-arrival time is well approximated by an exponential distribution, where the arriving aircraft flies further than the circle around 150 NM radius. However, the inter-arrival times converge to a nearly Gaussian distribution toward the arrival airports.

The empirical coefficient is defined as $C_e = \sqrt{\sigma_A}/\mathbb{E}[A]$, where $\mathbb{E}[A]$ and σ_A are the mean inter-arrival time and variance of the inter-arrival time. When $C_e \rightarrow 1$, the empirical distribution of the inter-arrival time is well approximated by an exponential distribution. If C_e is much larger or smaller than 1, then the empirical distribution is deviating from the exponential distribution. According to the empirical data, $C_e = 0.4688, 0.6467, 0.8089, 0.8125$ corresponding to 50, 100, 150, and 300 NM radii of concentric circles.

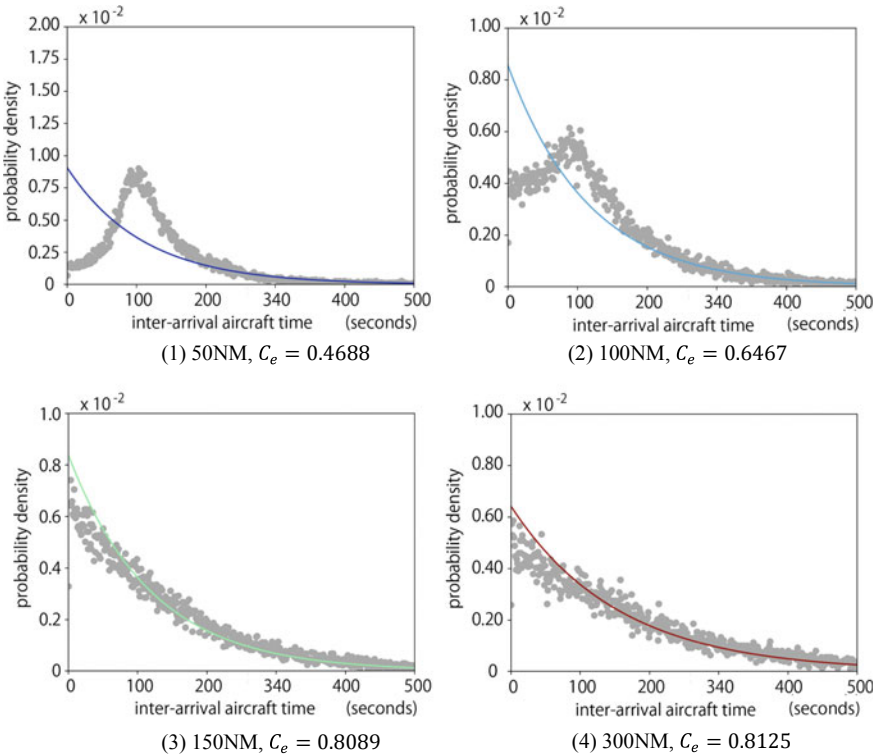


Fig. 5 Empirical distribution of the aircraft inter-arrival time and exponential fittings [10, 11]

5 Exploring Control Strategies in Future Arrival Management

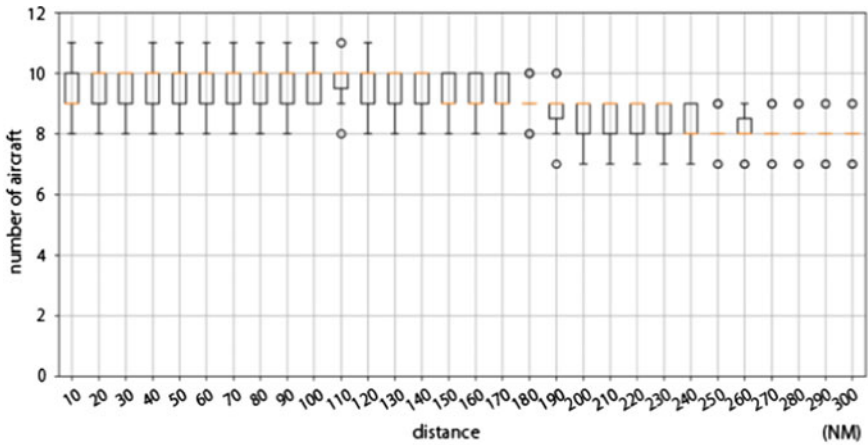
5.1 Shifting Air Traffic Control Flow to Time-Based Traffic Management

One of the important arrival strategies to determine is where and how the aircraft arrival flow shifts to time management toward the arrival airport while minimizing arrival delay time. The first author's study clarified the best arrival strategy based on the analysis applying data-driven queuing models [10–12]. The proposed queue-based approach demonstrated that there are five parameters, which impact on arrival delay time as follows: (1) arrival traffic rate (2) airspace capacity (3) mean of aircraft flight time (4) variance of aircraft flight time (5) variance of aircraft inter-arrival time. All five parameters were estimated through data-driven analysis using the two years radar tracks and flight plans. Mean and variance of aircraft flight time, and variance of aircraft inter-arrival time were analyzed in Sect. 4.2 as shown in Figs. 4 and 5.

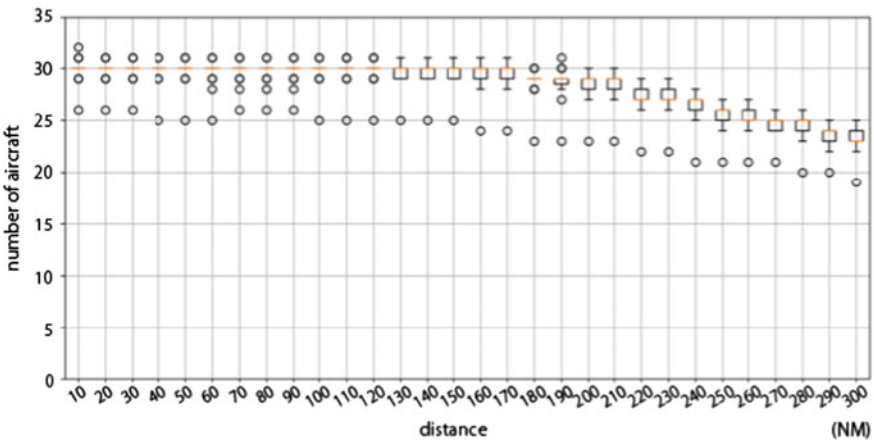
Figure 6 summarizes current arrival traffic rate in an hour at each concentric circle with 10–300 NM radii every 10 NM, focusing on arrival traffic from the north and southwest direction during the most congested time period 17:00 to 22:00 based on the data statistics. Arrival rate is well controlled at each airspace during the most congested time period; approximately, 10 aircraft from the north (see Fig. 6a) and 30 aircraft (see Fig. 6b) from the southwest arrives within 150 NM radius concentric circle in an hour [12].

Table 1 counted the number of aircraft from the southwest direction, which flew in the defined airspace, every 10 min during 17:00 to 22:00 time period in the two years. The values are relevant from operational point of views; 7 NM separation was given to arrival aircraft at 30–40 NM away from the airport before entering terminal area; thus, the number of aircraft between 30 and 40 NM radii concentric circles was 1 (see median value at 30–40 NM in Table 1.)

Approximately, 5 NM separation was given to initial approach fix, so the median took two aircraft in 10–20 NM and 20–30 NM airspace (see Table 1). In the queuing model, these values directory define the capacity at the assigned airspace. Based on the proposed queue-based approaches [10–12], the best arrival strategy to minimize arrival time delay is increasing airspace capacity within around 50 NM radius range. Extending aircraft flight time (with delay time) is more effective, where the variances of inter-arrival time are smaller, thus absorbing aircraft arrival delay closer to the airport is relevant operation for mitigating arrival delay time in the current arrival operation. According to the results of stochastic analysis using real data, the boundary to a fully deterministic time-based stage lay at around 30 NM away from the Tokyo International Airport. Transition area between the flow-based and time-based stage lay in-between 30 and 150 NM from the airport. Airspace further than 150 NM away from the airport could be assumed as the flow-based stage. However, the proposed queue-based approaches [10–13] showed that the best arrival strategy was shift these



(1) Arrival traffic from the north direction, 17:00-22:00



(2) Arrival traffic from the south-west direction, 17:00-22:00

Fig. 6 Arrival rate in an hour [12]. **a** Arrival traffic from the north direction, 17:00–22:00. **b** Arrival traffic from the southwest direction, 17:00–22:00

boundaries and transition area backwards: the boundary to a fully deterministic time-based stage at around 70 NM and the transition from the flow-based stage at further than 150 NM way from the airport.

Table 1 Arrival aircraft numbers served in the assigned airspace

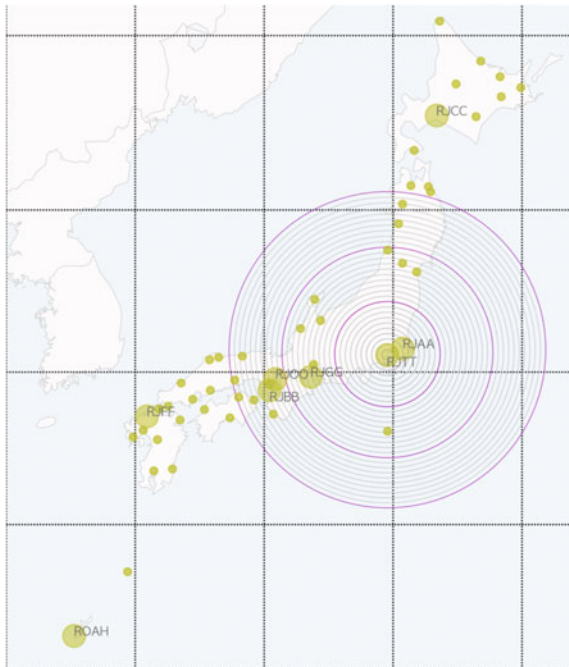
Airspace (NM)	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
median	2	2	1	2	1	1	1	1	1	1
mean	1.79	1.85	1.38	1.66	1.52	1.10	0.908	0.875	0.812	0.819
STD	0.809	0.971	0.649	0.882	0.914	0.808	0.753	0.746	0.758	0.793
Airspace (NM)	110-120	120-130	130-140	140-150	150-160	160-170	170-180	180-190	190-200	200-210
median	1	1	1	1	1	0	1	0	0	0
mean	0.773	0.792	0.723	0.693	0.676	0.647	0.683	0.585	0.593	0.581
STD	0.801	0.861	0.790	0.802	0.794	0.779	0.806	0.745	0.734	0.771
Airspace (NM)	210-220	220-230	230-240	240-250	250-260	260-270	270-280	280-290	290-300	
median	1	0	0	0	0	0	0	0	0	
mean	0.807	0.555	0.654	0.627	0.542	0.603	0.518	0.626	0.536	
STD	0.837	0.715	0.804	0.783	0.744	0.755	0.699	0.739	0.709	

5.2 *Uncertainties in Time Management Due to Pop-Up Aircraft*

Although smaller variances of aircraft flight time and inter-arrival time mitigate arrival delay time under limited airspace capacities, uncertainties in aircraft time management increases in further airspace from arrival airport. One of the causes anticipated is the impact of pop-up aircraft departing within the considered horizon from the arrival airport, which merges into air traffic flow. As shown in Fig. 7, Osaka International Airport (RJOO) and Kansai International Airport (RJBB) locate between Fukuoka International Airport (RJFF) and Tokyo International Airport. Figure 3 also indicates that arrivals from these airports take a large amount in total amount of arrivals at Tokyo International Airport.

In order to analyze the impact of pop-up aircraft departing from RJOO and RJBB, Fig. 8 compares growth of standard deviation (STD) in flight time since the aircraft departing from RJFF, RJOO, RJBB, Naha International Airport (ROAH), and Asian countries crossed the 200NM radius circle centered at Tokyo International Airport. Figure 9 compares the horizontal and vertical track records in a day. Although variances of flight time impacted by the total amount of flight, Fig. 8 shows that the STD corresponding to arrivals from RJFF grows between 130 and 160 NM, where departing flights from RJOO and RJBB merge into traffic departing from RJFF. As

Fig. 7 Distributions of airports in Japan



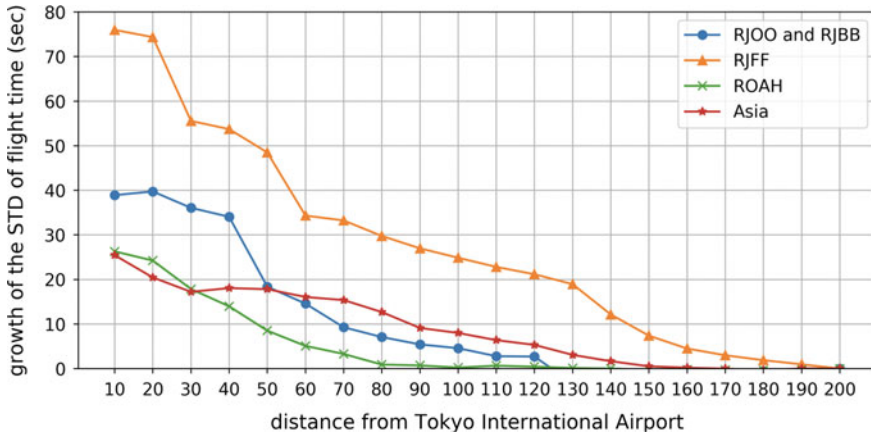


Fig. 8. Comparing growth of the flight time STD from these at 200NM

shown in Fig. 9, flight tracks of RJFF, RJOO, and RJBB merge not only horizontally, but also vertically below 30,000 ft airspace.

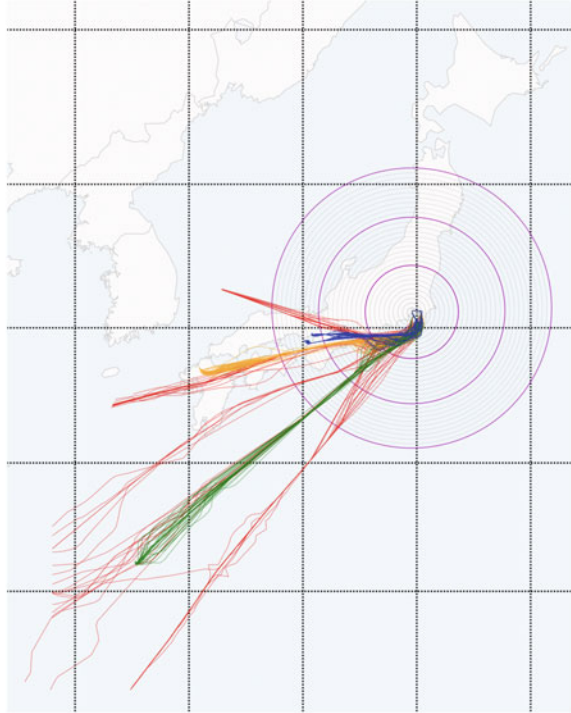
6 Discussion

This section discusses efficient arrival management strategies which can be applied in the stages of a multi-stage AMAN architecture (see Fig. 1) proposed in Sect. 3 based on the data-driven analysis in Sects. 4 and 5, and the first authors' work in [10–12].

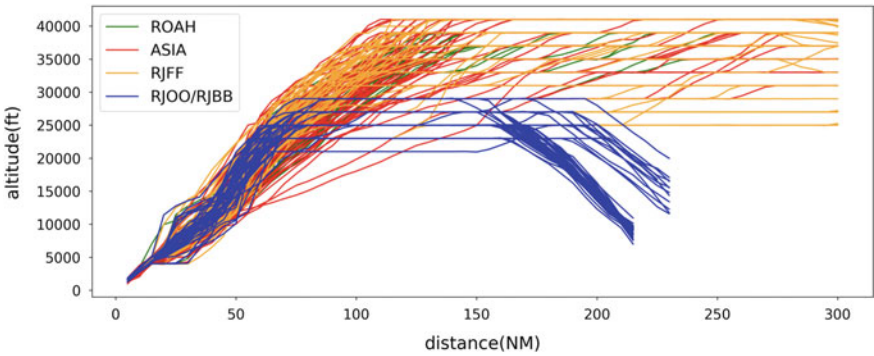
Firstly, the best arrival strategy in the stage 1 is increasing airspace capacity, especially 30–50 NM distance from Tokyo International Airport for minimizing arrival delay time. This control would be done by achieving time management of aircraft inter-arrival time at around 70 NM from the arrival airport in the stage 2, suggested in [10]. Freeze horizon, where the AMAN calculates the optimal arrival schedules, is required to lie in the stage 3 prior to achieve arrival scheduling. Aircraft trajectories would be controlled between the freeze horizon and horizon, where time management is required to achieve.

Secondly, total aircraft arrival delay time is reduced if the flight time is extended in the airspace area, where the variance of aircraft inter-arrival time is smaller. As shown in Fig. 5, the variance of the inter-aircraft time grows in the farther airspace area from the arrival airport, and the distribution is near exponential at the airspaces farther than 150 NM. One of our future challenges is to propose the best way to draw horizons, which tailor arrival aircraft traffic prior to the conventional freeze horizon, in stage 3 and/or stage 4.

Thirdly, again it is repeated but controlling aircraft flight time, which increases the variance of aircraft flight time in arrival traffic flow, is allowed, where the variances



(1) Horizontal records



(2) Vertical records

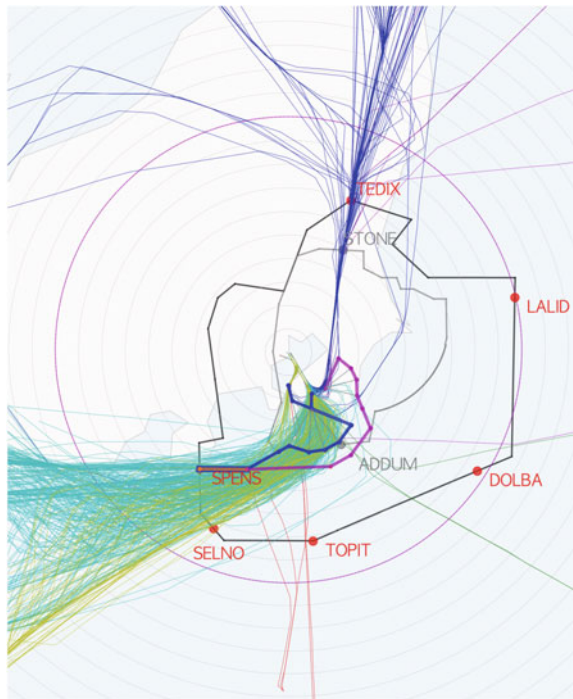
Fig. 9. Flight tracks of arrival aircraft from RJFF, RJOO, RJBB, ROAH, and Asian countries in a day. **a** Horizontal records, **b** vertical records

of the inter-aircraft time is smaller. Otherwise, arrival delay time of the total arrival traffic increases. This also means that trajectory optimization targeting individual aircraft is not the solution to achieve minimum aircraft arrival delay because of the interference with surrounding traffic. Trajectory-based operation needs to be designed in order to reduce the variance of inter-arrival times in the arrival traffic.

Fourthly, pop-up aircraft also impacts on increasing the variances of aircraft flight time. Further, study will analyze the impacts on the arrival traffic delay and solutions to mitigate the impacts.

Lastly, applying new wake turbulence minima, so-called RECAT (Wake Turbulence Re-categorization), and point merge operation influences in the stage 1. Point merge operation is introduced in arrival traffic at Tokyo International Airport since July 2019. Figure 10 shows an example of point merge routes applying to arrivals from southwest direction, with flight tracks of arrivals in a day in 2017 and concentric circles drawn every 10 NM radius. There were two transition points named ADDUM and STONE previously; however, six transition points are newly prepared according to the expansion of terminal area. As shown in Fig. 10, the arcs of point merge routes locate within 50 NM radii concentric circle. Authors' future work will also analyze the impacts of the RECAT and point merge operations on the arrival aircraft traffic.

Fig. 10 One of the representative point merge operation at Tokyo International Airport



7 Conclusions

This paper introduced a multi-stage arrival management concept and discussed stage boundaries based on a data-driven analysis. Two years of data consisting of radar tracks and flight plans of air traffic arriving at Tokyo International Airport were analyzed as a case study. The analytical results characterized arrival traffic flow at each stage in the proposed concept. The best arrival strategy was discussed to shift air traffic flow control to time management. Authors' future works further discuss the efficient design of arrival management in each stage.

Design requirements of arrival management system depend on the characteristics of a given arrival air traffic flow and its surrounding environment, e.g., runway and airspace capacity, weather conditions, air routes, and other geographical constraints. This study further designs the multi-stage arrival management not only at Tokyo International Airport, but also different airports, e.g., German airports and conduct interoperability analysis in future.

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