Data-Driven Analysis of Inefficient Arrival Separation

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Maintaining flight separation is key to ensuring safety in aircraft arrival operations. While sufficient separation is required for flight safety, excessive separation during peak hours can lead to reduced air traffic system capacity, extra arrival delay, and undesirable fuel burn. To maintain flight safety and accommodate high traffic volume, traffic flow guidance strategies (TFGS) are deployed to adjust flight landing time through extra flight distance. Previous studies have established the key factors affecting the separation deviation. However, gaps still exist in identifying inefficient separation, which can be mitigated by altering the air traffic management strategy. In this study, we extract flight trajectory features such as flight separation, standard arrival routes, and TFGS from ADS-B flight trajectory data. Through these features, we establish the effect of TFGS on arrival flight separation deviation. We characterize inefficient arrival separation through trajectory features, separation deviation, and traffic information. We also quantify the back propagation effect of the inefficient separation, in which the negative impact is not limited to a single flight. Our investigation based on air traffic data pertaining to the Hong Kong International Airport reveals that a notable portion of arrival flights have elements of inefficient separation; hence, there is room for improvement. The associated back propagation effect is also prominent. It can affect up to 20% of the daily arrival flights, and on average increase their time spent in terminal maneuver area by 15%. Our study provides an atomic evaluation on arrival separation analysis that can serve as a guide to improve air traffic management operations.

I. Introduction

The runway arrival capacity problem has imposed challenges on many airports globally, with insufficient capacity leading to extended airborne flight delays. Clear relation has been established between arrival wake separation and airport capacity [1, 2], with shorter and more precise wake separation being gradually implemented in airports to increase runway capacity [3]. While the wake separation requirement is a limiting factor of runway capacity, Andrews and Robinso [4] pointed out that the constrained maximum capacity is not always achieved even during peak periods due to excessive separation between flights. Imprecise separation between flights at landing can lead to runway capacity loss. The accumulated excessive deviation could have been used to accommodate additional arrival flights. Yet, not all separation deviations are avoidable, such as when traffic volume is low, longer separation is expected. To accurately characterize and quantify arrival inefficiencies, inefficient separation deviation should be isolated from the unavoidable separation deviation.

A. Wake Turbulence and Air Traffic Management Solutions

Wake turbulence separation is a mandated safety procedure to ensure sufficient spacing between successive flights to avoid wake turbulence-induced control issues and potential structural damage. This separation is executed by the pilots under the guidance of the air traffic controller (ATCO). The minimum separation for each flight is determined by the aircraft type of both the leader and the follower. O'Connor *et al.* [5] pointed out that the wake separation requirement at the time (2001) was only necessary during adverse weather conditions, therefore was too conservative in most situations. It is also demonstrated that the reduction in wake separation can lead to an increase in airport throughput and a reduction in delay, using their proposed system. Re-categorized wake separation rules (RECAT) are gradually being adopted around the globe to provide a more robust standard. The official report claims that the refined categories can improve the throughput by more than 5% during peak periods [6].

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To absorb a high volume of arrival traffic while maintaining sufficient wake separation and radar separation between arrival flights, various air traffic management solutions (ATMS) are used to adjust individual flight trajectories. These solutions are mostly based on the same principle that the arrival flights are guided, sequenced, and separated inside the terminal maneuvering area (TMA). As the time required for landing an aircraft is restricted by the wake separation standard, the larger the difference between arrival demand and airport capacity in the same period, the larger the magnitude of ATMS is required. ATCOs often use arrival trajectory strategies such as vectoring, short-track, and holding patterns to adjust individual arrival timing. In this paper, these strategies are collectively referred to as the *traffic flow guidance strategies* (TFGS). Problems associated with TFGS include ATCO workload and extra fuel consumption as some of the maneuvers are not standardized and rely on verbal commands from ATCO [7]. The point-merge technique was structured by Boursier *et al.* [8] to manage the spacing and sequencing of flights with an envelope of possible paths and a merge point. Simulation results produced by Ivanescu *et al.* [7] and Boursier *et al.* [8] supported that the point-merge technique can reduce the number of trajectory instructions, late vectoring, and fuel burn. However, initial findings by Hardell *et al.* [9] showed that airport operates using the point-merge technique has a higher trajectory distance than the corresponding reference trajectory. In addition, the controller's peak workload is also higher than the airport using the conventional TFGS system. The ATCO workload at the late stage of the arrival under point-merge is comparable to that of TFGS which reflects that the trajectory adjustments required in both systems are similar. Therefore, the point-merge technique does not prevent separation deviation. The paper authors acknowledged that the difference is not solely attributed to the difference in ATMS and a fair comparison should include the traffic conditions. A similar solution named trombone sequencing and merging was proposed by Sprong [10] and was shown to achieve lower flight time and distance. However, the initial findings presented by Hardell *et al.* [9] also demonstrated that the ATCO workload is considerably higher at the late stage of arrival which implies more adjustments are required at near landing stage and thus also does not prevent separation deviation. Wing *et al.* [11] presented a more direct approach to reduce separation deviation called the automated self-separation with airborne surveillance technology. The study demonstrated that automated self-separated flights with trajectory information can achieve better separation accuracy and separation loss conflict resolution. Scharl *et al.* [12] demonstrated a solution that combined the required time of arrival (RTA) and path discretization in TMA. The method improves the temporal and spacing accuracy of arrival flights by controlling arrival timing at waypoints through place-bearing-distance command.

B. Separation Deviation

Separation deviation, also known as spacing buffer, refers to the difference between the required separation (wake separation) and the actual separation when the leading aircraft lands. The spacing buffer is described as an additional spacing to reduce ATCO workload due to spacing variability [4, 13, 14]. However, since this difference in our study can be positive or negative, we refer to it as separation deviation in this paper. Arrival separation deviation is used as a performance indicator in air traffic management research and has been thoroughly studied in statistical modeling and runway capacity analysis [4, 9, 15]. Studies based on different airports generally produce similar statistical distribution but different parameters suggest that the arrival separation deviation characteristics are not universal [4, 15, 16]. Negative separation deviation at landing is a violation of safety regulations but is commonly observed in related studies [4, 15]. The negative deviation is associated with weather, radar accuracy, and traffic volume. Insufficient separation can increase the chance of a flight initiating a go-around maneuver [17] which is undesirable from airport capacity, ATCO workload [18], and operating cost standpoints [19]. Meanwhile, positive separation deviation is reflecting idle runway capacity. To maximize runway capacity, the amount of positive deviation should be minimized. However, part of the positive separation deviations are due to low traffic flow, which the extra separations are unavoidable, the idle capacity could not be used in serving extra arrival flights. Therefore, it is common in separation deviation research that the low traffic volumes data are excluded [15, 20].

To understand this inefficiency, studies have examined traffic factors with historical air traffic data from major airports around the globe. In their work, Spinoso *et al.* [15] have demonstrated that the arrival separation deviation can be affected by traffic factors such as operations in other runways. Separation deviation is also associated with factors such as weather, location [21], and area navigation capability [14]. These factors are crucial in determining the roots of separation deviation. An inverse trend between traffic volume and separation deviation has been validated in multiple studies [20, 21]. Minimization of the separation deviation is therefore necessary, as accurate separation allows higher utilization of the runway. This trend also implies that the separation deviation can be controlled. The control is associated with the ATCO and pilot as demonstrated in the works of Gu *et al.* [20] and Wing *et al.* [11], respectively. The separation between arrival flights is the result of interaction between the ATCO and pilots, whose strategy and decisions can influence the separation deviation. Christien *et al.* [22] demonstrated the effect of the sequencing pressure on the separation deviation. The sequencing pressure was defined as the arrival flight density in different time-from-arrival horizons. When the number of flights to be sequenced upstream is higher than that of downstream, ATCO intervention is required. This method, while combining the efforts of sequencing and separation management, is too general to quantify individual flight trajectory adjustment, which is one of the key criteria of inefficient separation. The current landscape of studies on arrival separation deviation can benefit from a closer examination of the effect of air traffic management strategies.

C. Inefficient Separation

With the goal of maximizing the utilization of runway capacity through separation deviation minimization, ATMS is deployed. During high arrival traffic demand periods, the deficiency in runway capacity calls for ATMS to be used in arrival sequencing and flight separation. These solutions can incur extra fuel consumption, travel time, and distance, therefore should be administrated discreetly [9]. Ren and Clark [23] highlighted the negative impact of ATMS in the separation correction context. In an ideal case, ATMS should adjust the flight separation to be the same as the required wake separation (i.e., zero separation deviation). ATMS as a measure to directly adjust the separation and the arrival time, has influence on separation deviation, thus a parameter to be considered in the identification of inefficient separation.

The sequencing pressure proposed by Christien *et al.* [22] also combined a reactionary effect due to trajectory adjustment of the leading flights where the impact of excessive separation is not confined to a single flight. When a leading flight has extra separation or trajectory adjustment, the closely following flights have to adjust their trajectories accordingly to maintain sufficient separation. This propagating effect is highly undesirable, as extra time, fuel and, ATCO instructions are required. Although the individual adjustments and negative effects are small, the aggregated amount can have an extensive negative impact that is not reflected in the arrival volume. The effect is not readily visible without measuring individual trajectory deviations. In our study, this effect is identified and measured quantitatively using the same name, *back propagation effect*, as proposed by Christien *et al.* [22].

Although studies have acknowledged the problem of separation deviation, as well as the fact that some are unavoidable, but the inefficient separation has yet to be isolated. In addition, previous studies have yet to establish the relation between ATCO-induced flight trajectory adjustments (ATMS) and separation deviation. This study aims to identify individual inefficiency among separation deviation by characterizing contradictory actions and redundancy. We also investigate the back propagation effect, which is a collective inefficiency and the hidden cost of separation deviation. Afterwards, we provide a quantitative overview of the inefficiencies using the Hong Kong International Airport (VHHH) as a case study. The case demonstrates that inefficiency exists even in world-leading aviation hubs and is notable enough to call for solutions to address the problem. This study also serves as a bridging solution to improve the runway capacity without significantly modifying the air traffic management system or the infrastructure.

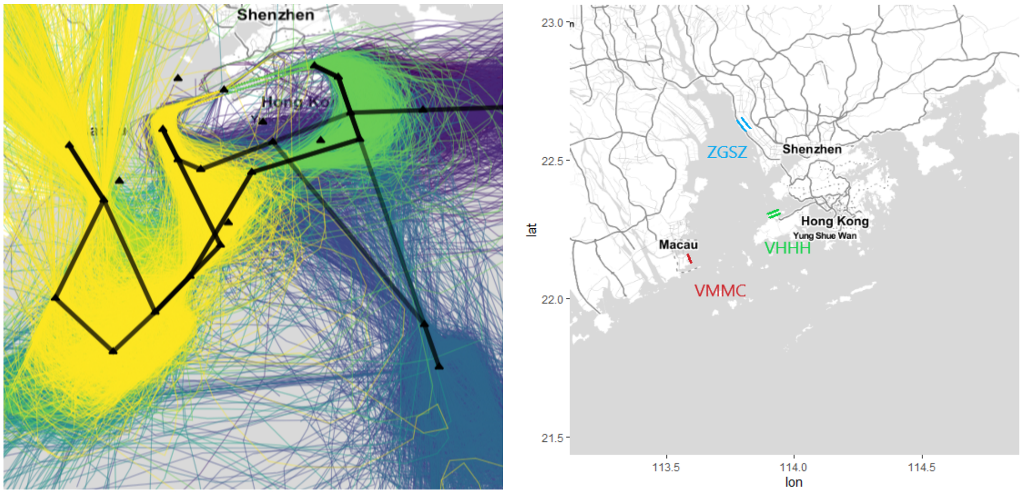
II. Data and Methodologies

To validate the proposed methods in our study, we conduct a case study on VHHH. In this study, we adopt a data-driven approach using automatic dependent surveillance-broadcast (ADS-B) flight data. The trajectory information and traffic dynamics are captured through data aggregation and feature extraction.

A. Flight Data Description

ADS-B is a flight surveillance technology that automatically broadcasts real-time flight information from the aircraft. The three-dimensional position data and basic flight information are broadcasted through this system periodically. Through ADS-B data and algorithms, aggregated traffic dynamics, individual flight trajectories, trajectory features, and separation between arrival flights can be extracted. In our study, 49 days (May 1st, 2018 to June 18th, 2018) of VHHH arrival flight data are used. The dataset consists of over 25,000 arrival flights into Hong Kong. A *trajectory pooling method* is developed to recover flight data with missing identification information. Using speed, horizontal distance traveled, vertical rate, and vertical distance traveled, we group the flight data with missing information and recovered 5% of daily arrival flights that would otherwise be discarded. The flights with missing information in our test case are usually associated with general and business aviation (GBA). These aircraft transmit a minimal amount of ADS-B information, possibly linked to the corresponding equipment mode. The recovery of missing flights is important to our study of separation inefficiencies as these GBA flights constitute the bulk of light aircraft (referring to the wake separation category) that operate in Hong Kong. In addition, missing flights can affect our quantification of back propagation as the identification of the affected flight depends on a complete continuous flight schedule, in which case a missing flight would present an excessive separation gap. Normal ADS-B is broadcasted at up to one flight message per second interval. The dataset we use in this study has an average message interval of approximately 60 seconds. The large gap between consecutive flight messages presents a challenge in capturing flight features and comparing the locations and separation between flights in a single time frame. As a result, we linearly interpolate the flight data (longitude, latitude, altitude, and heading) to one-second intervals from their entry into TMA until landing at VHHH. The short interval is necessary for the separation analysis. The interpolation does present inaccuracy to a small extent as the flight trajectory is straightened and does not represent the most accurate dynamics between flights. Overall, linear interpolation is not a perfect solution but is still an improvement upon the original set of data.

VHHH, as the target of the case study, presents some interesting features. VHHH is one of the busiest international air transportation hubs in Asia, it processed over 428,000 flights in 2018. According to Hong Kong Legislative Council [24], the designed capacity of VHHH is 420,000 flights per year, therefore the actual processed flight exceeded the designed capacity of the dual runway airport. To cater to such a vast volume of traffic, the dual runways (2018) were frequently under high traffic pressure and, logically, should have less separation deviation between the flights. As lower traffic periods are excluded from our separation deviation investigation, the constant high traffic volumes in VHHH can help us retain the majority of the data set. Another feature of VHHH is the restrictive geographical location and airspace. Situated in the Pearl River Delta, VHHH is located at the northern edge of the Hong Kong Flight Information Region (HKFIR) with flight restrictions to the west and north due to the proximity with Macau IA (VMMC) and Shenzhen IA (ZGSZ) (as illustrated in Fig. 1). This airport layout presents a routing challenge that can also be found in other airport clusters. In such a layout, flight paths cannot overlap with those of the neighboring airports, which limits the space for the ATCO to sequence flights and adjust flight trajectories. These features are common in metropolitan airport clusters where demand for air transportation is high and a single airport is insufficient. These features set a great environment for air traffic separation study as the arrival routes are packed closely together.



(a) Multiple days of arrival traffic inside the VHHH TMA. STARs connected in black lines, and arrival trajectories are colored by their respective STAR.

(b) Map of Pearl River Delta with the three major airports highlighted.

Fig. 1 Air traffic overview and clustered airport locations.

The area of investigation is narrowed to the TMA of VHHH. The TMA is a smaller area inside the HKFIR enclosing the airport. The Standard Arrival Routes (STARs) are contained in this area, along with the majority of the arrival flight sequencing efforts. To capture the sequence and separation dynamics, a slightly larger geographic box is used. Flight data outside this box are excluded from this study.

B. Separation Pair and Separation Deviation

For flight f and the leading flight $f-1$, separation deviation $\Delta\gamma^f$ is the difference between the actual separation $\gamma^f_{\tau^{f-1}}$ and the required arrival wake separation $\omega^{f-1,f}$, where τ^{f-1} is the time flight $f-1$ crosses the airport boundary. While $\omega^{f-1,f}$ is available in the list of wake separation category, the calculation of $\gamma^f_{\tau^{f-1}}$ is less straightforward. The calculation begins with the identification of landing pairs, the leader $f-1$ and the follower f. As the flights from different STARs are merged near the end of the STARs, the landing pairs can change. The landing pair should not be deduced by the actual landing sequence as go-around flights can be the leader of two or more landing pairs but only recorded once in the landing sequence. As a result, we use a more dynamic method to find the landing pairs to ensure the correct separation pair as well as capturing an accurate dynamic of the separation evolution. For a follower flight f, we find the closest flight in front at every time-step among the seven pre-defined possible options:

1) Go-around flight, the last detected go-around flight
2) $f-1$ landed flight, the flight that lands before flight f
3) $f-2$ landed flight
4) $f-3$ landed flight
5) $f-4$ landed flight
6) Last landed flight that uses the same arrival route
7) Last landed flight that uses a similar segment of arrival route

At each time step (one second), the leader $f-1$ is the flight in front of flight f with the lowest separation. Using this method, the leader-follower pair for each flight is not constant and better represents the separation before merging. The method is also compatible with go-around flights. Flight f's actual separation of $\gamma^f_{\tau^{f-1}}$ is calculated when its immediate leader arrives at the landing threshold. The actual landing spot was not used here as our ADS-B data has long intervals which is unreliable in determining the exact landing location. A common solution in arrival separation research is to set an arrival threshold on each runway as the landing point. As VHHH's runways are parallel and staggered, a rectangular box touching the four runway thresholds (two runways, two directions) and enclosing the airport is used. We measure the crossing time τ^{f-1} and use it as an index to measure $\gamma^f_{\tau^{f-1}}$.

We understand that the combined effect of data interpolation and landing threshold substitution can reduce the accuracy of the separation calculation, therefore deviation in low magnitude should be regarded as accurate separation. The separation deviations at lower traffic volumes are not as meaningful as the deviations are mostly due to insufficient traffic and therefore unavoidable.

C. Trajectory Features and Extraction

ADS-B data contains abundant flight information as well as disorganized flight features that can be unraveled with feature extraction algorithm. These features are crucial in characterizing flight trajectory and factors that affect separation deviation. In this study, five major features and aggregated traffic situations are extracted to be used in the evaluation.

1. Standard Arrival Routes (STARs)

STARs is a set of published arrival paths that guide the arrival flights from the en-route phase to the approach fix. The STARs include sets of waypoints, speed limits, and altitude limits. This information can reduce the workload of ATCO, avoid mid-air conflicting traffic, and facilitate flight merging. Arrival flights are to follow an assigned STAR, but the specific STAR information is not captured in ADS-B. The identification of individual STARs is key to the identification and quantification of path adjustment in the later sections.

While the modern flight system is capable of accurately following the STARs, the ATCO and pilot have the discretion to deviate if necessary. Holding pattern, vectoring, and short-track are the common traffic management features that require deviation from the STARs. The closely packed STARs and different extents of path deviation pose a challenge in the identification of STARs in each flight trajectory. The core algorithm of this identification is the aggregated shortest point-to-line distance between the flight trajectory points and STARs segments. The advantage of this method is that the point-to-line distance performs better in clustered STARs. We locate the STAR that is closest to the flight trajectory and identify it as a match. Artificial aids such as waypoint extension, intersecting lines, and trajectory cutting are used to enhance the accuracy of the algorithms.

2. Holding Pattern

Holding pattern, also known as racetrack procedure, is a circular trajectory TFGS often used in the airspace of Hong Kong to extensively delay the landing of individual flights. The maneuver can enclose a large amount of extra flight time within a small airspace and therefore is commonly used when an extended delay is required. The magnitude of the delay is, however, rigid when compared to other TFGS. Full completion of the maneuver, in general, takes six minutes. Furthermore, breaking off from the pattern during the process is not advisable, as the action would require additional guidance from the ATCO. The pattern is usually executed at the edge of the TMA at a higher altitude to preserve fuel and avoid conflicts. As an upstream maneuver, the holding pattern's ability to create accurate separation at the runway is limited and vulnerable to external factors such as neighboring flight maneuvers and weather. Therefore, flying in a holding pattern can result in separation deviation if not coupled with other path adjustment methods.

In this study, the detection of a holding pattern relies on the consecutive change in heading. Since our data have a long message interval of one minute per message, and the typical time of a full holding pattern is six minutes, we add one minute to both ends. Therefore, in any consecutive eight minutes, if the cumulative change in heading exceeds the threshold, a holding pattern is identified. An example of the identified holding pattern in VHHH TMA is illustrated in Fig. 2(a).

3. Vectoring

Vectoring, also known as path stretching, is an angular trajectory TFGS commonly used in Hong Kong airspace to moderately delay the landing of individual flights. The maneuver guides the flight off the STARs, and by covering extra distance, the separation between flights and arrival timing can be adjusted. Although the maneuver usually takes place at a few locations along the path, the extent of the deviation appears to be flexible and at the discretion of the ATCO to create sufficient time and separation between flights. The maneuver can be executed near the airport during the approach phase to fine-tune the separation and is therefore less vulnerable to external factors. However, underuse or overuse of vectoring can still result in separation deviation.

The extraction of vectoring in this study relies on the comparison between the flight trajectory and the identified STAR. For flight f with a discrete trajectory sequence $(t_i^f)_{i\in[1..n_f]}$, n_f is the number of trajectory points corresponding to flight f. For segment $\overline{t_i^f t_{i+1}^f}$, we project t_i^f and t_{i+1}^f onto the identified STAR segment with minimal distance. We then calculate a distance difference $\Delta d_i^f = dist(t_i^f, t_{i+1}^f) - \rho_i^f$, where ρ_i^f and $dist(t_i^f, t_{i+1}^f)$ represent the projected distance and the actual distance traveled, respectively. Lastly, by inspecting consecutive three distance differences (i.e., $\{\Delta d_{i-1}^f$, Δd_i^f, and $\Delta d_{i+1}^f\}$), if the amount of positive distance difference exceeds a threshold, we can conclude that the segment is on a vectoring maneuver. This method inspects individual segments for the differences in distance which returns the most accurate result. We experiment with lateral deviation, heading dynamics, and overall distance difference methods, but the projection method returns the best resolution and quantification properties (i.e., the actual distance difference). Combined with the flight speed, we can translate the distance into travel time for subsequent evaluation use. An example of the identified vectoring in VHHH TMA is illustrated in Fig. 2(b).

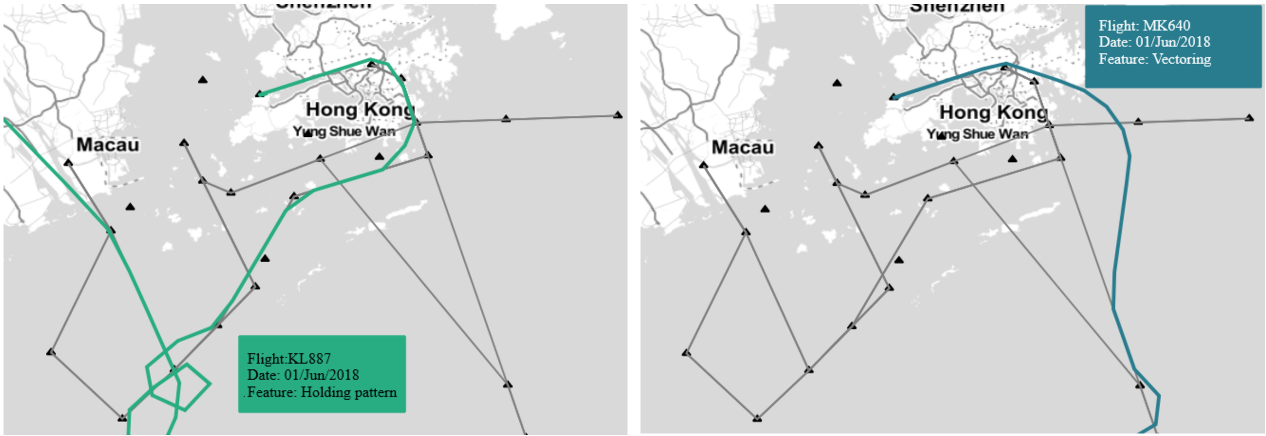
4. Short-track

Short-track is the opposite of vectoring and is used to shorten the trajectory by angular trajectory adjustment. The maneuver also guides the flight off the STARs to cover less distance to accelerate the arrival process. Short-track is usually executed by skipping waypoints or segments. Short-track does increase the flexibility of air traffic management, but the distance skipping also involves altitude changes that may not be applicable in some traffic scenarios.

The extraction of short-track is similar to that of vectoring but focuses on negative segment distance differences. The projection method is designed to cater to the extensive path-skipping scenarios where multiple waypoints and segments are skipped.

5. Late Path Adjustment

The main observed functions of path adjustment (vectoring and short-track) are separation adjustment and sequencing, but determining which function each path adjustment served is challenging. Since we are interested in understanding the effect of path adjustment on separation deviation, we want to isolate the path adjustments that serve flight separation purposes. To differentiate the path adjustment for sequencing purposes and separation adjustment, we only count the path adjustment at the late stage of the arrival. The extent of this late-stage segment is derived through testing and



(a) Flight trajectory with Holding Pattern

(b) Flight trajectory with Vectoring

Fig. 2 Example flight trajectories with special flight features. STARs are shown in gray lines.

observation, it should be adjusted accordingly in different locations. By extracting the path adjustment executed in the later part of the STARs, we can have a better understanding of the interaction between path adjustment and separation deviation.

All the adjustments to each flight are summarized into individual *late path adjustment* parameter, which is the summation of all path distance deviations within the end part of the STARs. This distance is also coupled with the corresponding flight speed to translate into late-stage flight time deviation.

D. Other Traffic Features

Traffic volume is one of the major factors influencing the separation deviation and hence, its effect has to be isolated in order to evaluate the other targeted factors. The purposes of traffic volume measurement are to reflect the ATCO workload, the number of flights to be landed, and the pressure on the air traffic system. Various methods are used in this measurement. Baren *et al.* [21] measured the number of flights 10 NM before the runway threshold which, in the case of VHHH, can exclude some combinations of flights even at minimum wake separation (3.5 NM in 2018). Hardell *et al.* [9] and Christien *et al.* [22] used a metering and sequencing effort to quantify the change in air traffic sequence at multiple time horizons from landing. A common method in air traffic studies is to measure the number of flight operations on the runways within a time interval. Gu *et al.* [20] used a fixed 20-minute operation volume with a five-minute overlap. In this method, consecutive flights would share the same traffic volume. The method has less flexibility in reflecting a sudden surge in runway operations. Therefore, in our study, we use an individual ±15-minute arrival volume to determine the pressure on the traffic system. The traffic volume is calculated for each flight at the time of crossing the threshold. This method is easy to compute, reflects the arrival demand within the same period, and is comparable to the declared capacity of the airport. The declared hourly capacity of VHHH is 68 movements per 60 minutes [24]. Since the airport operates in independent arrival and departure mode on parallel runways, the capacity for arrival should be 34 movements per 60 minutes. We deem ±30-minute traffic volume too broad to reflect the traffic pressure for individual flights, therefore a period of ±15 minutes is used. The respective traffic capacity in this time interval should be seventeen arrivals. Exceeding this capacity is possible and not rare, but the most observed traffic volume is exactly the declared traffic capacity of seventeen arrivals in any ±15-minute period.

III. Results and Analysis

In this study, we yield five major results. In Section III.A, we analyze the general separation performance of VHHH, and establish that there is room for improvement in the arrival operation. In Section III.B, we examine the usage and trend of TFGS in VHHH. The results also establish the corrective effect of TFGS to arrival separation deviation. Using the extracted trajectory and traffic features, in Section III.C, we characterize the inefficient arrival separation. Then, we quantify the extent and impact of the inefficiency in VHHH. In Section III.D, the flights with identified inefficient separation are subjected to further analysis and visual trajectory inspection to identify the factors that attribute to the deviation. Lastly, in Section III.E, we further examine the propagation effect of the inefficient separation deviation. We demonstrate that the negative impact of inefficient arrival separation is not limited to the single flight and can propagate to the subsequent arrival flights. Afterwards, we present the characteristics and the impact of the affected flights.

A. General Separation Deviation and Late Path Adjustment Analysis

Using the method described in Section II.B, we generated VHHH's separation deviation distribution, as shown in Fig. 3. While the distribution shape resembles the log-normal distribution presented in the work of Spinoso *et al.* [15], the negative deviation in VHHH is much more dominant than those in previous research. Spinoso *et al.* [15] reported a 5.9% negative separation deviation, Andrews *et al.* [4] reported a 7.6% negative separation deviation, but our data show over 25% of the separation deviation in VHHH is negative. The number increases to over 30% if only high-traffic volumes period are included. The negative separation deviation is also more prominent during higher traffic levels, potentially associated with higher runway usage. When the traffic level increases, the mean and variation of separation deviation decrease and converge towards zero (as illustrated in Fig. 4(a)). The phenomenon is documented as *the compression effect* in the work of Herrema *et al.* [13]. The effect is also associated with increased runway throughput as the utilization rate increases. However, we also observe that the amount of positive separation deviation in VHHH remains high at higher traffic volumes which indicate some slacks in the system. It should be noted that the accuracy of our calculation can be limited by the data interpolation and landing position approximation.

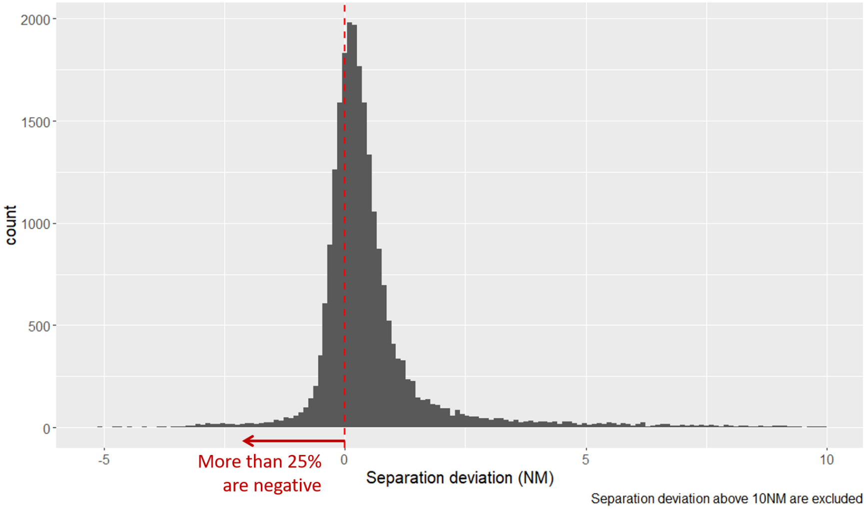
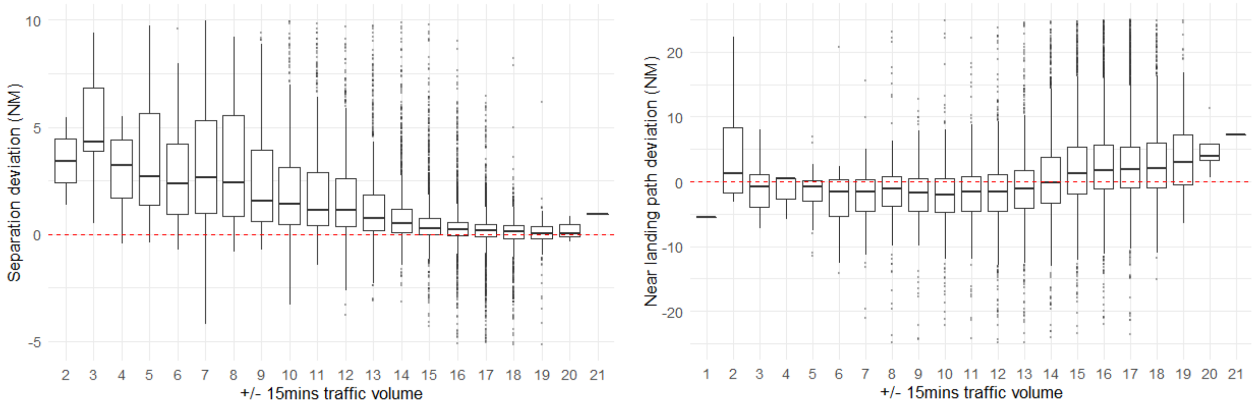


Fig. 3 The distribution of arrival separation deviation in VHHH.

In contrast to the separation deviation, the late path adjustment in VHHH exhibited a different distribution shown in Fig. 4(b). The use of late path adjustment increases with traffic volume. In lower traffic volumes (< 14 arrivals in ±15-minute), the majority of the late path adjustment is below zero, which indicates the use of short-track to accelerate the arrival. As traffic increases, the average late path adjustment increases beyond zero. The positive late path adjustment indicates delays and potential insufficient arrival system capacity. The use of late path adjustment at traffic volumes lower than the maximum traffic level indicates inefficiency to some extent. Although the path adjustment is a necessary tool in air traffic management, the inefficient use of it cannot be ignored and needs to be reduced to improve the overall efficiency.

B. Effect of TFGS on Arrival Separation Deviation

Key functions of TFGS are the sequencing and adjustment of radar separation and wake separation. In other words, the flight separation is adjusted towards zero separation deviation using TFGS. The magnitude of the adjustment should be based on the specific needs. It is worth noting that certain situations can limit the effectiveness of TFGS in adjusting separation deviation. For example, a short-track can only shorten the path to a certain extent and might not be able to fully eliminate separation deviation. The result would be a positive separation deviation at landing. Fig. 5 shows the density distribution of separation deviation against late path adjustments. The density exhibits an airfoil-like shape with



(a) Arrival separation deviation trend

(b) Late path adjustment trend

Fig. 4 The trend of extracted features under different traffic volume

a blunt end on the left and a sharper end on the right, akin to the leading and trailing edge of an airfoil, respectively. At near zero late path adjustment (*x*-axis), the separation deviation is the largest in magnitude, implying that when there is no late path adjustment, the separation deviation is the largest. As the late path adjustment increases in magnitude, the spread of the separation deviation decreases gradually and converges toward zero, implying that late path adjustment has the ability to adjust separation deviation. This effect can be found in all traffic volumes as illustrated in Fig. 6. The results conform with the hypothesis that the TFGS is a factor of the separation deviation. As TFGS is controllable by the ATCO, the separation deviation can also be mitigated with the revised administration of TFGS.

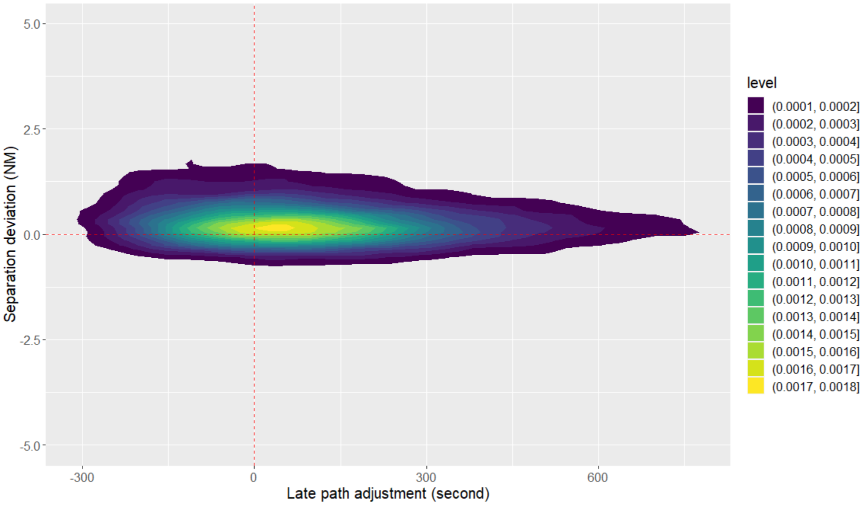


Fig. 5 The effect of late path deviation (in seconds) on arrival separation deviation. Traffic volumes ranges from 13 to 18.

C. Inefficient Arrival Separation

Ideally, the amount of late path adjustment should be just enough or less than the amount required to offset the separation deviation to zero. The remaining difference can be further adjusted by speed control. However, any adjustments more than the amount required, especially those that might result in positive separation deviation, should be avoided as they not only induce extra travel distance but also undermine arrival capacity.

As previously mentioned, not every separation deviation is avoidable. When such cases are encountered, they should be excluded from the evaluation of air traffic system inefficiency. In this study, we propose the following criteria for

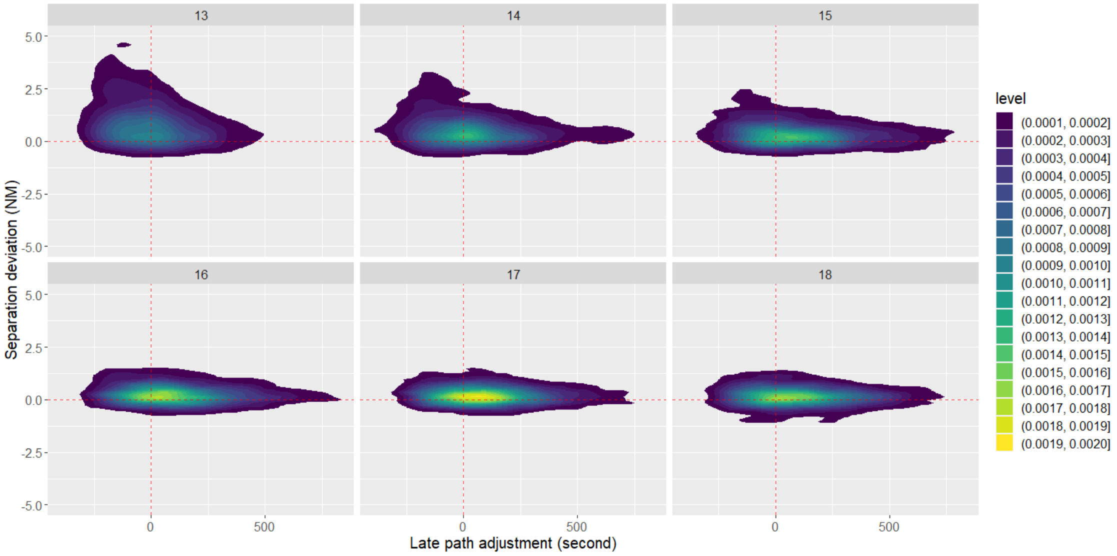


Fig. 6 The effect of late path deviation (in seconds) on arrival separation deviation is represented in different traffic levels (13-18 / ± 15 minutes).

characterizing inefficient arrival separation:

1) High traffic volumes
   As separation deviation is sometimes unavoidable in low-traffic demand, the identification should be limited to higher-traffic volume when arrival capacity is insufficient and arrival delay is expected. The separation deviation then becomes a factor in determining the efficiency of the separation. In our analysis, we define high traffic volumes as more than 14 arrivals in any ±15-minute period (i.e., more than 80% of the designed arrival traffic volume). However, it is important to note that the traffic volume alone is not a decisive factor in determining an inefficient separation deviation. Inefficient separation deviation is also possible during low traffic volumes when other conditions are met. The inefficient separation at low traffic volumes has lower impacts on arrival system capacity but can create arrival delays and the need for path adjustment. In our analysis, we only consider the inefficiencies under high traffic volumes as the arrival capacity is a major factor in this investigation.
2) Positive separation deviation
   Positive separation deviation is undesirable at high traffic volumes as it reduces runway capacity. The threshold of positive separation deviation in this study is set to 1 NM to account for calculation errors and potential separation buffer. To put this into context, the minimum wake separation in VHHH in 2018 was 3.5 NM.
3) TFGS - Holding pattern and vectoring
   With the effect of TFGS on separation deviation established, the amount of TFGS assigned should be just enough to neutralize separation deviation. A positive separation deviation when positive path adjustments are applied is deemed excessive and inefficient. There are two types of positive TFGS in our study, vectoring and holding pattern. This condition can be satisfied with either one being positive.

Using the above criteria, we check every arrival flight during the day to evaluate the performance of VHHH's arrival separation. Fig. 7 shows the analysis of a single day's flight in VHHH. Each column represents the separation deviation of an arrival flight. Their location on the "Time" axis is their approximated landing time. The spacing between each and previous column is the actual time separation between arrival landings. Flights with all inefficient separation characteristics are highlighted in green. The accumulated deviation can reduce runway capacity and prolong arrival delay of the subsequent flights.

Fig. 8 shows the aggregated impact of inefficient separation on arrival traffic. The different columns indicate the corresponding cause of the inefficient separation. Our analysis shows that the portion of flight involved in inefficient separation varies but can be more than 10% of the daily flight. The four colored bars represent different method of measuring inefficient separation. Light green and yellow bars represent the portion of inefficient separation among all traffic volumes associated with vectoring and holding pattern, respectively. Dark purple bars represent the portion of inefficient separation (vectoring and holding pattern) among flights under high traffic volume. Dark blue bars represent

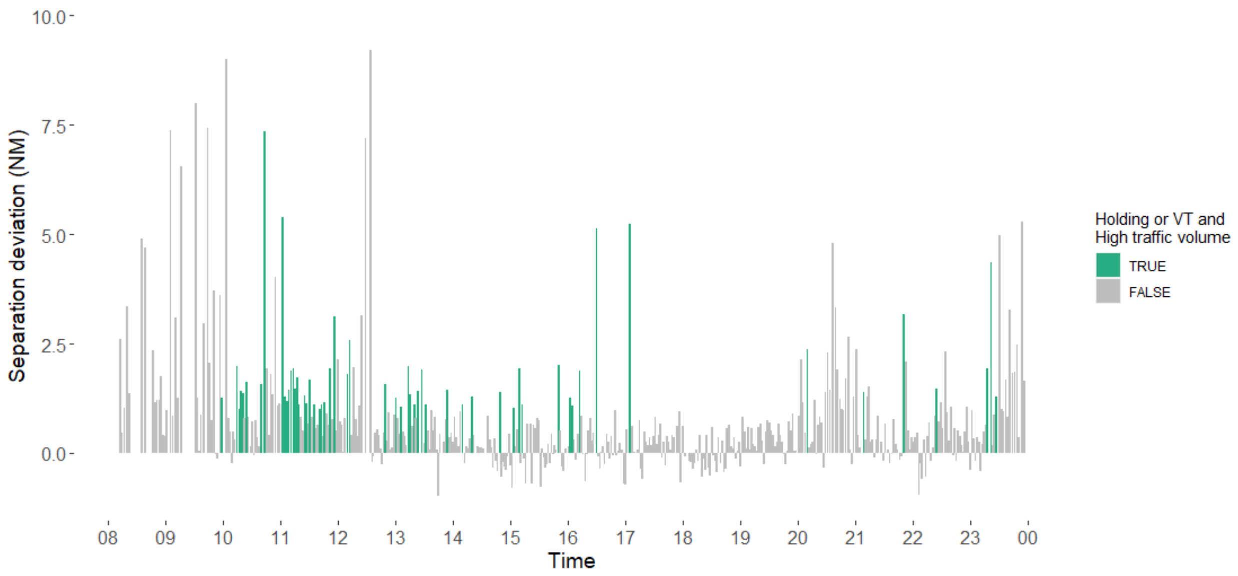


Fig. 7 Arrival separation analyses for flights arriving at VHHH on 12 June 2018. Inefficient separations are highlighted in green (separation deviations beyond 10 NM are not shown).

the portion of inefficient separation (vectoring and holding pattern) among all arrival flights. The values of these two methods are similar in all observed dates as the airport was under high volume of traffic during most of the operation time. The dotted lines overlay in Fig. 8 show the daily proportion of inefficient arrival separation deviation (all traffic volumes and both vectoring and holding pattern, dark blue bars) that operate during adverse weather phenomenon (right y-axis). Van Baren *et al.* [21] highlighted the variation in separation deviation (spacing buffer in their work) under different weather conditions. A higher deviation is observed when the wind is stronger. These near airport weather conditions are reported by the METeorological Aerodrome Reports (METARs). We define a significant weather phenomenon category to include adverse weather phenomena such as gust, low visibility (Instrument Flight Rules condition [IFR]), precipitation, and other adverse conditions. These conditions can potentially affect flight performance. In our analysis, the conditions are grouped into three major categories, namely wind, visibility, and significant weather features. We observe that, occasionally, a high proportion of inefficient separation happens during adverse weather phenomena (e.g., May 10 & June 13) but further analyses reveal that neither the frequency nor the magnitude of separation deviations are correlated with the investigated adverse weather phenomena (as illustrated in Fig. 18 in Appendix A). In the works of Lui *et al.* [25] and Zelinski [26], it is demonstrated that weather can affect arrival transit time and arrival pathing. Ren and Clarke *et al.* [23] highlighted the impact of wind on separation and how it should adjusted accordingly. The weather effect, however, appears to be well accommodated in Hong Kong's traffic management system as it has no observable effect on separation deviation.

In our observation, the daily aggregated separation deviation ranges from 9 NM to 440 NM, with an average of 68 NM. These inefficiencies occurred separately, and therefore can be aggregated and used to accommodate additional flights. The most common aircraft types operating in VHHH are "Medium" and "Heavy", the possible wake separations are 3.5 NM, 4 NM, and 5 NM. In other words, on average, the inefficient separation deviation is undermining the capacity of the runway by 2 to 3%.

D. Further Analysis on Other Causes of Separation Deviation and Mitigation Strategy

After identifying the inefficient separation deviation using the above criteria, we further the investigation by performing individual traffic dynamic inspections. This process relies mainly on manual observation of traffic dynamics of the flights preceding and succeeding the identified inefficient flights. In this process, we identify multiple causes of separation deviation that are associated with necessary processes. They are mostly limited by regulations and the physics of aircraft operation. Although associated with necessary processes, these deviations are mitigable through better planning and traffic control. In the following, we discuss some of the causes of separation deviation and possible

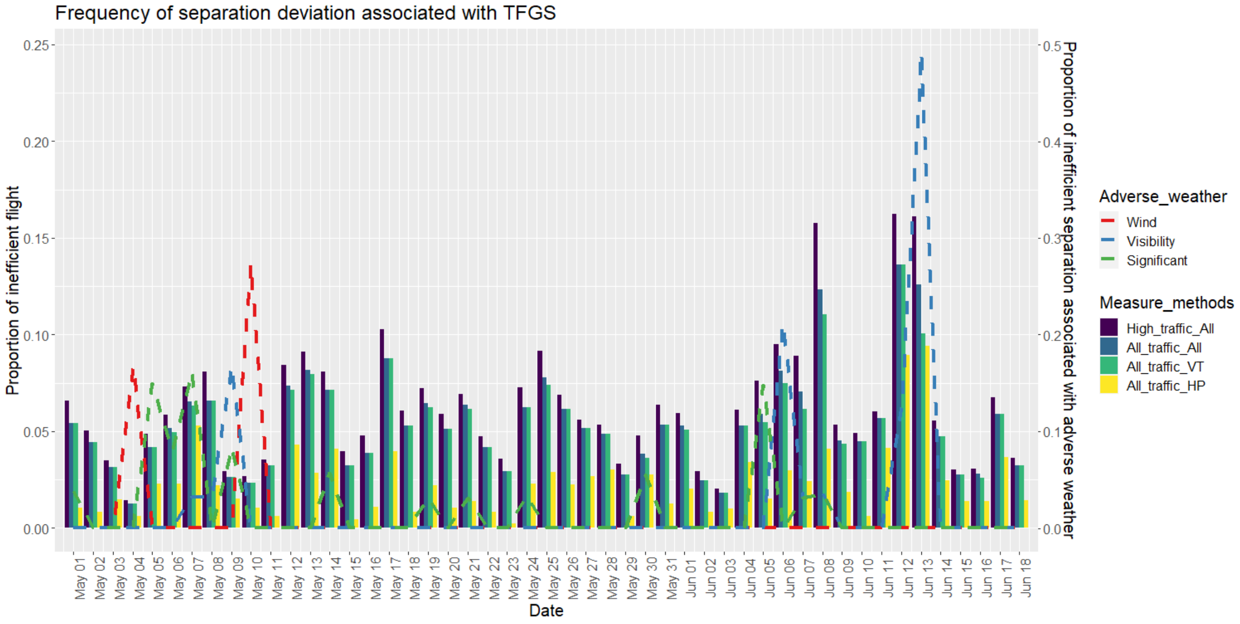
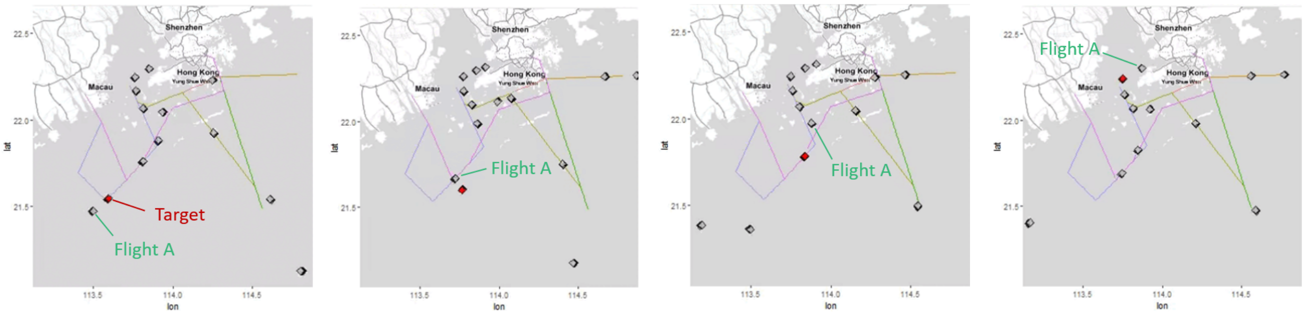


Fig. 8 The daily proportion of flight effect of inefficient separation.

mitigation strategies.

1) Landing direction switch
   To land in favorable conditions such as headwind or adhere to restrictions, the airport switches the landing direction. During the switch, the last flight before the switch and the first flight after the switch will fly in the opposite direction into the airport. To avoid hazardous scenarios and account for the potential go-around, the ATCO often creates an extra landing gap during the switch. While this separation deviation is noticeably large, it is unavoidable for safety reasons. This runway switching operation is infrequent in our observation, therefore the capacity lost is not significant. Under feasible conditions, the authority can reduce the capacity lost by coupling the switch with arrival scheduling, and schedule the switch between the nearest arrival pair with the highest wake separation.
2) Arrival timing
   In some cases, even if the follower flight takes the shortest path to the runway, positive separation still exists. The main attribute is the entry timing of the flight. The separation of the aircraft is also affected by the upstream factors such as the delivery timing into TMA from the flight information region. If the flight is delayed before entering TMA, the separation deviation can occur. In some cases, we observe that the delayed entrance into TMA is caused by the holding or delay maneuvers outside of the TMA. The inaccurate re-join (into TMA) timing, results in suboptimal arrival timing. Depending on the situation, short-track can compensate the deviation to a certain extend. This phenomenon can be mitigated with more precise re-join timing after extensive delay outside of the TMA.
3) Minimum radar separation
   Inside the TMA, the flight has to maintain a minimum radar separation from all other flights to avoid mid-air collision. This limits the extent of ATCO control over the arrival timing of flights and can result in separation deviation. Under feasible conditions, arrival sequence can be reordered to achieve better runway utilization if some of the leading flights are unable to achieve accurate separation delivery.
4) Rate of descent
   Due to the border issue and proximity to the other major airports, the northern HKFIR entrance point is very close to the airport and at a high altitude. Flights from this entrance point have to traverse extensive horizontal distance for a reasonable rate of descent. As a result, flights from the north cannot fully utilize short-track or speed-adjustment methods to expedite their arrival as they are limited by the rate of descent.
5) Fixed-length holding pattern
   Apart from being a factor of inefficient separation identification, TFGS can be the source of inefficient separation

as well. As discussed in section II.C.2, the execution of a full holding pattern takes six minutes, and early termination is not advised. The inflexibility of the holding pattern poses a challenge to delaying the flight while maintaining accurate arrival separation. In our observation, the use of holding pattern in arrival sequencing and flight delay can lead to positive separation deviation. The extra separation produced by holding patterns executed at the late stage of the arrival can be difficult to be compensated by other countermeasures such as short-track or speed adjustment. An example is illustrated in Fig. 9, the key traffic dynamics are captured in four instances. In the first instance (Fig. 9(a)), the target flight and a reference flight A enter the VHHH TMA with the target flight as the leader. Then, in the second instance (Fig. 9(b)), the target flight is guided off the track to execute a holding pattern to create extra separation for flight merging. After the holding pattern, in instance 3 (Fig. 9(c)), the target flight goes into the follower position of flight A with a noticeable long separation from the leader flight (flight A). The long separation is caused by the fixed length of the holding pattern. This extra separation can sometimes be reduced by applying short-track or speed adjustment. However, in this case, the holding pattern is very close to the landing which might not have sufficient time for the target flight to adjust the distance, which resulted in a positive separation deviation at landing (as illustrated in Fig. 9(d)). In a feasible situation, other TFGS (i.e., vectoring) should be considered before deploying the holding pattern.



(a) Both flights enter the TMA with target flight in front

(b) Due to flight merging, the target flight is directed to holding pattern to create space

(c) The target flight moved to the back of flight A after the holding pattern with noticeable extra separation

(d) Unable to reduce the narrow the spacing, the target flight has separation deviation.

Fig. 9 An example of holding pattern leads to extra separation deviation

E. Back Propagation Effect of Inefficient Arrival Separation

The effect of inefficient separation is not always confined within the inefficient flight and might have cascading effects to others, which calls for a systematic investigation. As the leading flight has extra separation, the subsequent flights have to adjust accordingly to maintain adequate separation. This adjustment in flight trajectory, although small for individual flights, can propagate extensively through the arrival sequence. The propagation is particularly prominent during peak periods when the arrival flights are tightly packed together with minimal extra spacing. The tight formation performs poorly in back propagation absorption. To identify this air traffic inefficiency, we propose the following criteria for characterizing back propagation effect as illustrated in Fig. 10:

1) Leading flight separation deviation (Case 1, condition 1 in Fig. 10)
   The back propagation effect begins with a flight with inefficient separation deviation. The extra separation disrupted the arrival flow by delaying the subsequent arrivals. The presence of a leading flight separation deviation (i.e., $\Delta\gamma^{f} \le 1$ NM) is important to measure the extent of each separation inefficiency as the affected flights are associated through their source of the back propagation effect. Flights affected by back propagation effect must have a leading flight that satisfy all characteristics of inefficient separation list in Section III.C.
2) Substantial late path adjustment (Cases 1 & 2, condition 2 in Fig. 10)
   The main effect of the back propagation effect is the path adjustment required to maintain sufficient separation. As path adjustment is also used in arrival sequencing purpose in earlier stage inside the TMA, we only measure those occur in the later part of the arrival trajectory inside TMA. In our observation, flights affected by back propagation effect often requires path adjustment at the base leg or the downwind section of the arrival approach. A possible explanation to this late reaction is that the separation deviation of the leading flight is only realized at the late stage. In addition, late adjustments are more effective in adjusting the arrival separation. Flights affected

by back propagation effect must have a certain amount of late path adjustment.

3) Subsequent flight low separation deviation (Cases 1 & 2, condition 3 in Fig. 10)
   After being path adjusted, the affected flight should have a low separation deviation with leading flight ($\Delta\gamma^f \leq$ 1 NM). The low separation also indicates that the traffic flow is tightly packed together that the extra separation has been exhausted in the absorption of the upstream inefficiency. In contrast, a significant separation deviation indicates that the flight is either unaffected by the back propagation or itself is an inefficient arrival separation.
4) Continuous sequence (Case 2, condition 1 in Fig. 10)
   To establish a chain of affected flights, the first condition can be substituted with an affected flight. If a flight meets the second and third conditions set above and the leader flight is an affected flight, it is classified as an affected flight as well. This substitution allows us to measure the extent of the back propagation. In this case, the second and third conditions are the stopping criteria. For example, a flight follows a sequence of affected flight but with $\Delta\gamma^f \geq 1$ NM or low late path adjustment is not classified as an affected flight, as the back propagation effect is either absorbed or did not extend to the flight.

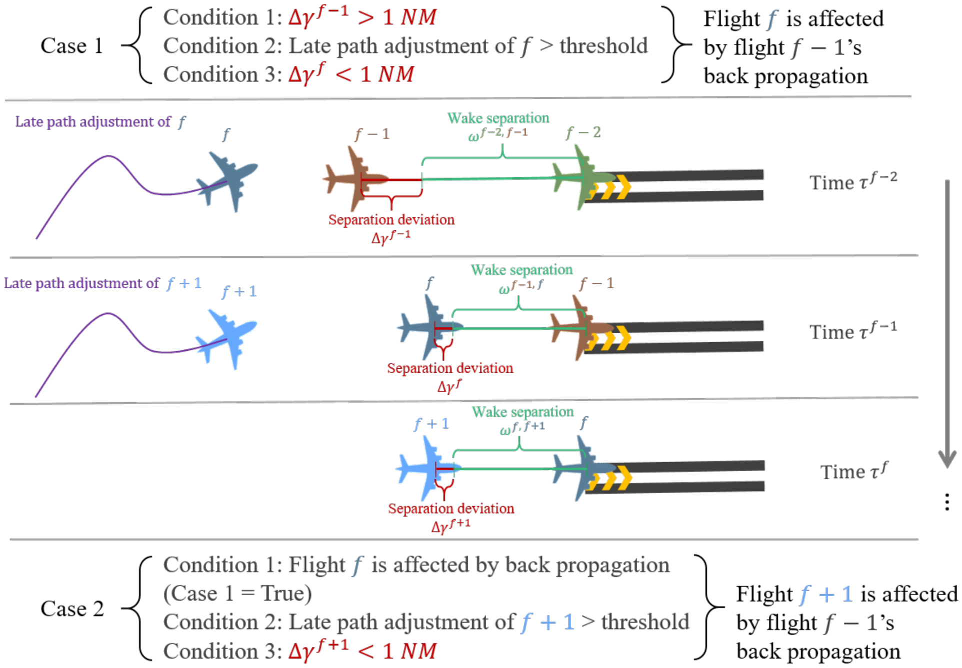


Fig. 10 An illustration of the two possible ways to identify back propagation effect.

Using the above criteria, we first check for inefficient arrival separation, then we check the subsequent flights for characters of the back propagation effect. Fig. 11 shows the effect of back propagation on a sequence of arrival flights. The dotted black lines are the segments of a STAR (SIERA7C), and the black triangles are the waypoints of VHHH. The exhibited trajectories are the flights that travel through the STAR segment. The trajectories colored in purple are flights that are unaffected by the back propagation while those colored in green are affected by the back propagation of the same flight. The unaffected flights have less positive late path adjustment, some of them even have short-track that accelerates their arrival. In contrast, the affected flights exhibit different degrees of vectoring near the base leg of their arrival. The extra distance covered in these adjustments is associated with the extra separation deviation of a leading flight. In this case, the average separation deviation of the twelve affected flights (by the same source) is -0.055 NM with none of them over 0.6 NM. The leader flight inefficient separation deviation, the follower flight positive late path adjustment, and the follower flight low separation deviation, these characters together form the elements of back propagation identification.

Fig. 12 highlights the flights that are affected by the back propagation effect in a full-day flight schedule. Each column represents individual separation deviation and they are colored if they are affected by the back propagation effect. Columns in gray are unaffected, while the affected flights are colored, with each color indicating flights affected by the same source of back propagation. On this day (14 May 2018), more than 20% of the arrival flights are affected

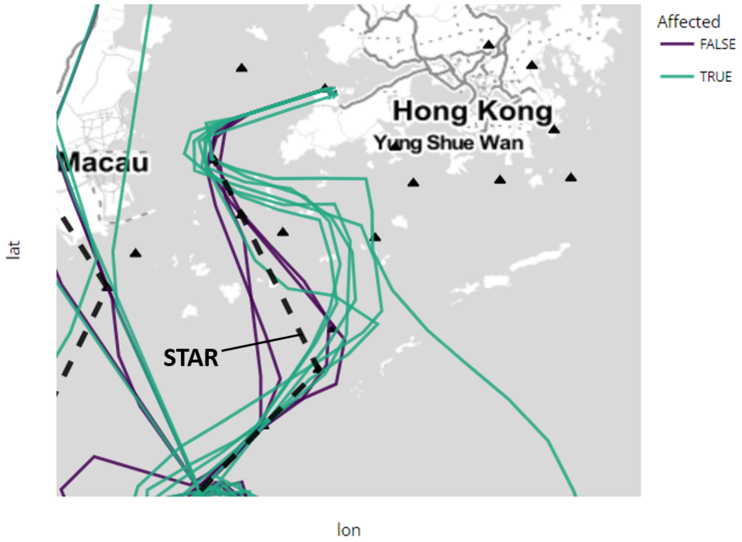


Fig. 11 The effect of back propagation on near airport flight trajectory.

by the back propagation effect, which is caused by 5.3% of arrival flights with inefficient separation deviation. For a macroscopic overview of this inefficiency, Fig. 13 shows the daily proportion of flight (top, blue columns) affected by the back propagation effect, and its extent in terms of aggregated extra distance traveled (bottom, green columns). The effect of back propagation varies, with over 20% of the flights affected on some days. Although the aggregated path adjustment (in distance) is insignificant (i.e., less than 500 NM for the entire day for the majority of them), these path adjustments occur at the final part of the arrival when the speed of the aircraft is low. Therefore, the low aggregated distance actually translates into a significant amount of travel time, and has a relatively large impact on individual traffic flow. Put the figures into context, the average flight time spent in TMA was 1,063 seconds. On average, every 1 NM longitudinal deviation is equivalent to 16.1 seconds of delay. On 7 May 2018, 27.5% of the arrival flights were affected by the back propagation effect, and the aggregated longitudinal deviation was 1,526.5 NM. The average arrival transit delay (extra flight time within TMA) of each affected flight was around three minutes. The total delay was more than 24,612 seconds. This aggregated extra travel time, however, does not fully translate into extra arrival capacity as some of them happen simultaneously. The significance of this inefficiency is that the effect can be extensive in high-traffic situations, path adjustment in limited air space can be challenging and a heavy burden for the ATCO, and the adjustment can also lead to extra fuel burn. As the effect originates from individual separation deviations, solving the delivery accuracy can alleviate the collective inefficiency.

F. Speed Control

On top of using TFGS, ATCO can also adjust the separation by managing the speed difference between successive flights. Various studies also used speed control methods as a component of their arrival solution. Ng *et al.* [27] demonstrated a method that incorporates arrival pathing [*] and cruise speed adjustment into arrival scheduling problem. The study highlighted the trade-off between arrival delay and cruise speed adjustment. Jun *et al.* [29] demonstrated an extensive range of delay transfer from TMA to the en-route stage through speed control. Using estimated descend time and predicted delay inside TMA, the approach delay can be absorbed in the en-route phase by speed reduction. The work also demonstrated the benefits in fuel and emission reductions through this method. The work of Delgado and Prats [30] highlighted that speed reduction in en-route phase can be achieved with similar or less overall fuel consumption. The work of Franco *et al.* [31] focused on speed and fuel trade-offs during cruise phase. They pointed out that advancing flight arrival through speed increment results in higher fuel consumption even when the flight time is reduced. Extending their finding, we believe the arrival advancement through speed increment at the approach phase can lead to a net increment in fuel consumption proportionally. The delay absorption in the en-route phase or prior alone is insufficient

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[*] Ng *et al.* [28] presented the alternative path method in another work. Using waypoints of the STARs, the method examines a number of alternate arrival paths to achieve lower overall arrival time while considering radar separation, weather, and other key factors in arrival path selection.

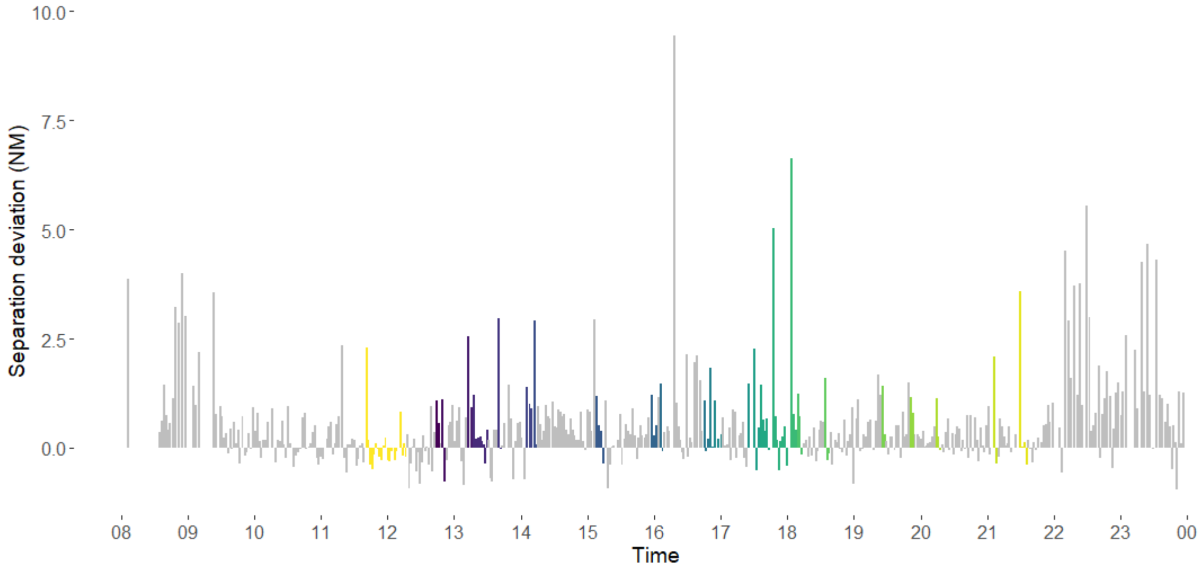


Fig. 12 Analyses results of the single day back propagation effect observed on 14 May 2018. Each color corresponds to a group of flights affected by the same flight (separation deviations beyond 10 NM are not shown).

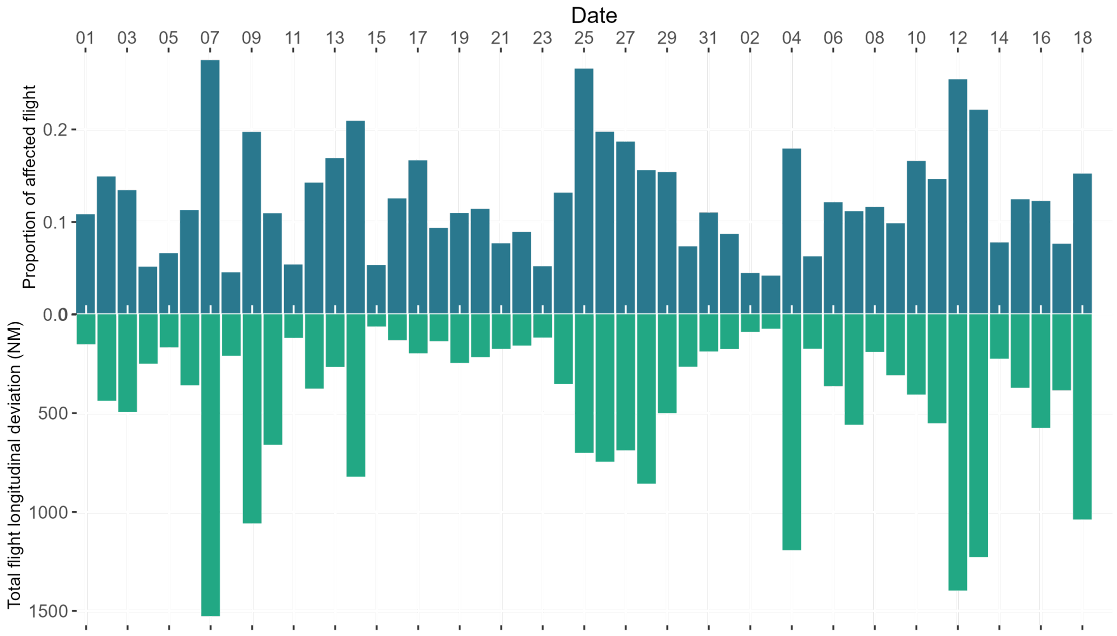


Fig. 13 Daily effect of back propagation (01 May 2018–18 June 2018).

because uncertainties in the TMA can lead to substantial aggregated and propagated delays. A possible countermeasure to separation deviation is the use of speed control during the final approach. The concern about speed control at the late stage of the arrival is the effect on flight performance. The work of Drinkwater and Cooper [32] pointed out that although higher approach speed offers better thrust and maneuvering margin, the accelerated approach can be undesirable due to amplified path error and longer stop distance. Within a reasonable range, the speed control can be used as a means to impose finer adjustments to the separation even at the late stage of the approach. The work of Barmore [33] highlighted the effectiveness of speed control in the mitigation of arrival separation deviations. The speed difference between the leader-follower pair is able to adjust the separation deviation towards zero in both human-in-the-loop flight test and fast-time computer simulations. The work of Itoh *et al.* [34] highlighted the effectiveness of speed control in mitigating the separation deviation under the Airborne Separation Assistance System (ASAS). The experiment of Wing *et al.* [11] presented that the separation can be better controlled when flights have access to the trajectory intent (including speed) of other flights. The previous studies summarized the speed control strategy as a trade-off between flight time and fuel burn. Although flight acceleration requires more fuel, the reduction in flight time and subsequent delay can justify the trade-off. In this section, we introduce an analytical method to determine whether speed control is applied to mitigate positive separation deviation in the TMA and to assess its effectiveness.

To determine whether speed control in mitigating positive separation deviation is applied, we define the flight speed parameters $(S_L^f)_{L\in(FAF,APP,LND)}$ for flight f at three separate locations L, where FAF, APP, and LND represent the final approach fix, approach, and landing, respectively. Here, *approach* is not a fixed location but a time-based relative position of the target aircraft when the leader flight crosses the airport boundary. These three locations are near the end of the arrival where sequencing no longer takes place, and the speed adjustment is more dedicated to the arrival separation and timing. Through the measurement of flight speeds in these three locations, we can evaluate the general speed trend of VHHH during the final approach. The distributions of speed at different location by wake separation category by landing direction is shown in Fig. 14.

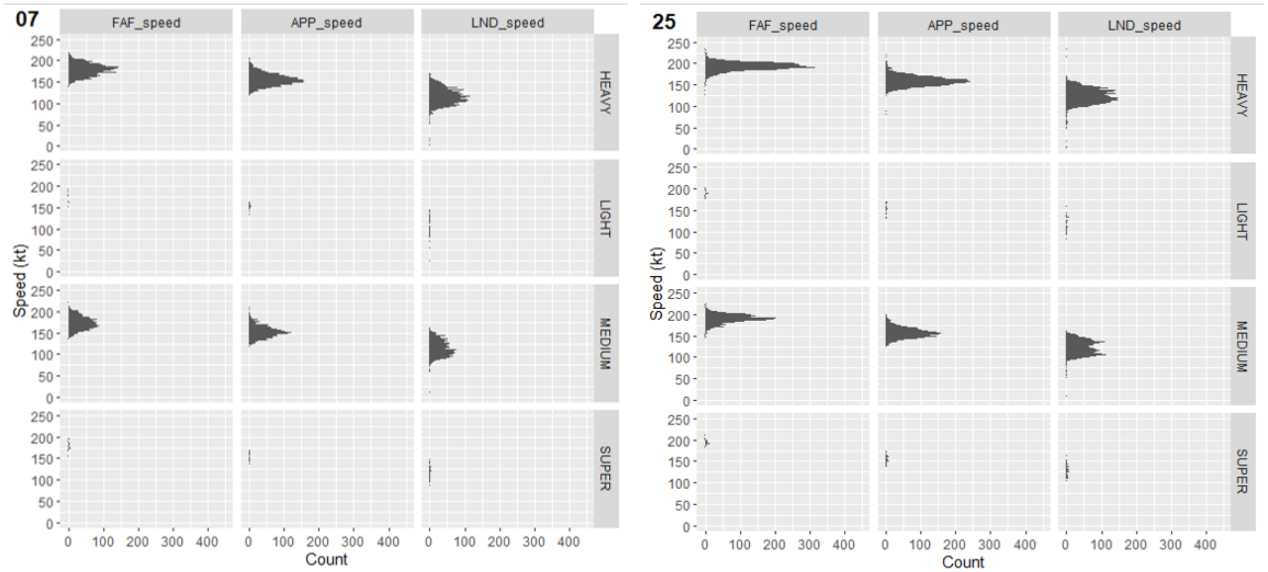
As the S_{APP} is measured at a time-relative position instead of a fixed location (S_{FAF} and S_{LND}), if the separation between the arrival pair is large, then the S_{APP} of the follower should be greater as it is further away from the airport. While our result is aligned with this deduction, however, we also observe that there is a portion of flights that has relatively low S_{APP} but significant positive separation deviation (as illustrated by the variable named APP_speed in Fig 15), which is the opposite of speed control in mitigating separation deviation.In Fig 15, the speed distribution at different location is further grouped by their separation deviation. To compare the change in mean speed, two dotted lines are placed, red (left, FALSE column) for those with separation deviation less than or equal to 1 NM, green (right, TRUE column) for those with separation deviation over 1 NM. The red lines are extended over to the the TRUE column for the ease of comparison. The part that we want to highlight are the portions of flights on the TRUE column that have speed lower than the mean of FALSE column (i.e., lower than the red lines).

Change in speed in terms of deceleration is a natural procedure during the approach. To isolate the speed control for separation adjustment from the "natural" deceleration, we convert S_L^f into standard score Z_L^f to understand if the speed is faster or slower than usual. By comparing Z of a flight in the three locations, we can derive the individual trend of speed adjustment that is relatively less influenced by the natural deceleration. The derivation of Z_L^f is as shown in Eq. 1.

$$Z_L^f = \frac{S_L^f - \overline{S_{LDW}}}{\sigma_{LDW}} \tag{1}$$

where D and W are the landing direction and wake separation category of flight f, $\overline{S_{LDW}}$ and σ_{LDW} are the mean speed and standard deviation of category W at location L in landing direction D. The reason for not using a unified average or standard deviation is the known difference in speed for different wake separation categories in different landing directions (as illustrated in Fig. 14). Except for landing speed, the other speeds are normally distributed. The sparse distribution of landing speed is potentially due to the interpolation error. The error arises from the long data interval where two consecutive trajectory data t_i^f for the landing speed estimation can have drastic speed change. In some cases, the first message is transmitted when the aircraft is still airborne, and the next one is transmitted when it is already on the taxiway. Our current data interpolation method is also vulnerable to large changes in speed. Therefore, the landing speed in this study is not used. When more accurate landing trajectory information is available, the incorporation of the landing speed in determining the exercise of speed control would be beneficial.

The standard score $(Z_L^f)_{L\in(FAF,APP)}$ provides insights into the speed control of the individual flights. Regardless of the speed of the leader flight, a follower flight with higher speed (or slower deceleration) during the final approach



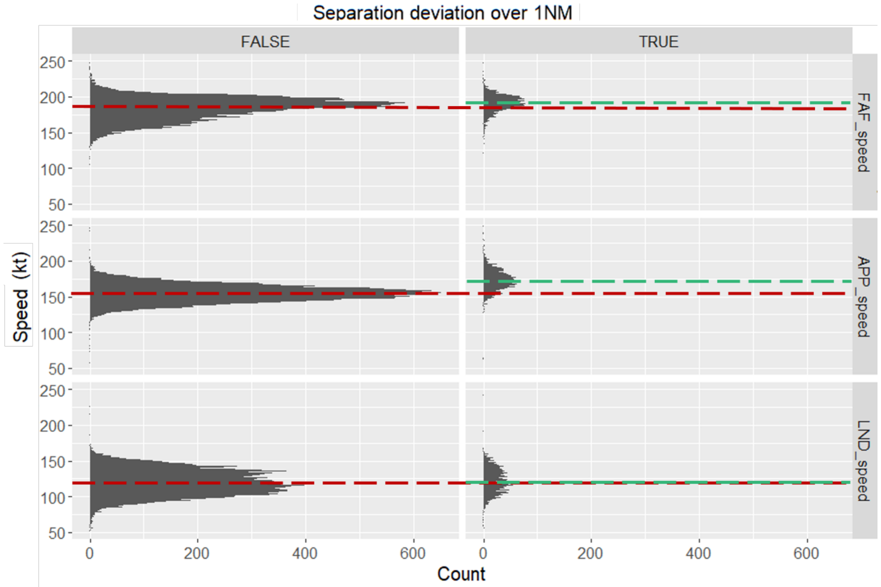
Flights under 14 flights per 30 minutes are excluded

Flights under 14 flights per 30 minutes are excluded

(a) Flight speed distribution at different locations by wake separation category in 07 direction

(b) Flight speed distribution at different locations by wake separation category in 25 direction

Fig. 14 There are observable difference in flight speed distribution in different landing directions, measurement locations, and wake separation categories.



Separation deviation above 10NM are excluded
Flights under 14 flights per 30 minutes are excluded

Fig. 15 Speed at different location by condition. Flights on the right column (TRUE) has separation deviation larger or equals to 1 NM.

can maintain or reduce distance with the leader flight. If speed control is applied to mitigate the positive separation deviation, both Z^{f}_{FAF} and Z^{f}_{APP} should be positive. In reverse, we can also identify the lack of speed control if the resulted separation deviation is positive, while both Z^{f}_{FAF} and Z^{f}_{APP} are negative. The result shows that more than 10% of the flight with more than +1 NM separation deviation during high traffic volumes has not exercised sufficient speed control. Further individual analysis is conducted on these identified flights, yielding the following observations:

1) Asynchronous speed adjustment
   For a flight pair $f-1$ and f, if the deceleration profile of $f-1$ is not the same as that of f, then the separation between the pair changes. The large differences between S_L^{f-1} and S_L^f along with positive $\Delta\gamma^f$ can indicate such phenomenon. To keep the separation towards the wake separation requirement, global speed control has to be applied. This observation is also aligned with the observation highlighted in the work of Wing *et al.* [11].
2) Tight turn and high speed
   The STARs of VHHH are packed with multiple 180° turns (as illustrated in Fig 1(a) and Fig 11). When short-track is applied, the flight cuts into the inside of the turn to complete the turn faster. In that case, the turn radius is reduced which might potentially limit the speed of the turn.
3) Short-track and descent
   Flights assigned with short-track can have reduced time for descent. To meet the altitude requirement, an increased rate of descent is used. If speed control is simultaneously applied to accelerate the arrival, then the time for descent is further reduced, and the rate of descent has to be further increased. Since the rate of descent is regulated, therefore speed control may not be applicable in some cases.

G. Rigid Arrival Schedule

During a conversation with an experienced pilot who operates in and out of VHHH, it is mentioned that the arrival manager system (AMAN) of VHHH tends to follow a rigid procedure in rearranging the arrival order when there could be better solutions. This phenomenon is dominantly experienced in the TMA where the arrival flights are in queues prior to landing. The lack of flexibility to change the arrival order can increase the overall delay and reduce the runway capacity. It is believed that, in particular situations, by switching the order of some flights, the overall delay can be reduced. The situation does not solely concern the change in total wake separation required, the delay and associated maneuvers have to be considered as well. Although the information given in the conversation was limited, we are able to characterize the phenomenon with the extracted features proposed in this paper.

In this investigation, we consider a discrete one-step swapping scenario where the swapping is possible between immediate leader-follower pair (in other words, swapping with two flights in front is not considered). This problem is commonly known as constrained position shifting (CPS) in flight schedule optimization problem. The problem has been well explored, examples such as the works of Balakrishnan *et al.* [35] and Rodríguez-Díaz *et al.* [36] have presented solutions feasible for live operation. Although these solutions are fast enough to be deployed in live operation, they remain in an ideal situation and can be vulnerable to dynamic operation factors such as flight delivery accuracy. The dynamic nature of the arrival environment can be benefited from arrival order swaps during operation within the TMA. With complete traffic trajectory information, we can identify the flights that could have been swapped for better overall delay and capacity.

Our investigation in the arrival scheduling considers the arrival separation deviation and late path adjustment to demonstrate the rigidity of the arrival schedule in the operational level. We hypothesize that this rigidity prevents the arrival sequence to be reordered for better overall traffic efficiencies such as arrival delay and runway utilization. The hypothesis of the rigidity can be validated by applying CPS to individual flights and examine if there are better alternative arrival sequence. Examining the characters of the flights that have better alternate sequence can give us insight into the future planning of arrival sequence or real-time arrival sequence adjustment.

To retain the uncertainty of traffic dynamics, the individual separation deviation is included in both the calculation of the original amount of time required and that in the swapped sequence. The late path adjustment of the follower flights is used to advance the flight in the sequence. The inclusion of this factor enables the near-landing swapping of the sequence that retains the individual separation deviation and serves as a quantification of the inefficiency behind the rigidity of the arrival schedule. The feasibility of the swap is determined through the change in time required to complete the landings, the shorter the better.

The calculation (as illustrated in Fig. 16) involves four consecutive arrival flights which are denoted as $f-2$, $f-1$, f and $f+1$ (in actual landing order), where f is the follower flight to be swapped with the leader flight $f-1$. The first part of the calculation is to derive the actual total time required to land these four flights which is the landing time of flight $f+1$ minus that of flight $f-2$, The second part is the calculation of the total time to land the four flights in the swapped sequence. In this scenario, the landing time of flight f is advanced in time by its amount of late path adjustment and cut in front of flight $f-1$. If the amount of spacing between flight f and flight $f-1$ after the advance of flight f is sufficient (for wake separation between flight f and flight $f+1$ pair), then flight $f-1$ lands at the original time. If not, then flight $f-1$ is delayed by vectoring until a sufficient amount of separation is achieved. Afterward, flight $f + 1$ is scheduled to be landed behind flight $f - 1$ in the swapped sequence. The extent of flight $f + 1$ advance in landing time also depends on the amount of late path adjustment it has. The earliest possible time of landing of flight $f + 1$ is that of flight $f - 1$ plus the original amount of separation deviation and the new required amount of wake separation. The swapping incurs three new leader-follower pairs and their respective wake separation. In the end, we calculate the new total landing time required under the swapped sequence and compare it with the original one. If the new time is shorter, then the swap is beneficial. This method assumes that the leader flight $f - 1$ retains at least the original amount of separation deviation and cannot land sooner than the original schedule. The benefit of this method depends on how soon the swapping is realized to be beneficial and executed.

The results presented in Fig. 17(a) show that more than 15% of the flight can benefit from arrival order swapping (i.e., as indicated by the negative change in total landing time after the swap, which is highlighted in green). Assuming that the switch takes place, an increase in total landing time after swapping is possible when the late path adjustment is insufficient to move flight f in front of the original flight $f - 1$ landing time. In the case where the flight $f - 1$ could not advance in landing time, the change in total landing time is equal to the wake separation between flight f and flight $f - 1$ after the swapping (spikes in Fig. 17(a) at around 100 seconds and 125 seconds), which must be avoided.

Examining the factors behind the swap, we found that the late path adjustments of flight f and flight $f + 1$ can be useful indicators of the benefit of the swap. In Fig. 17(b), we plot the swap benefit against the late path adjustment of flight f and found some interesting patterns. On the positive side of the y-axis, we observed a few grouped lines on the left side of the x-axis. The horizontal lines are the cases where flight f has negative late path adjustment (short-track), and the earliest time that it can land is the original landing time. Therefore, the change in total landing time is equal to the wake separation of flight f and flight $f - 1$ (i.e., $\omega^{f,f-1}$). As the flights operating in VHHH are dominantly medium and heavy flights (referring to wake separation category), the most visible lines are the four possible combinations of these two categories. For the diagonal lines, the flight f has positive late path adjustment, but is insufficient to advance the flight f beyond the original landing time of flight $f - 1$. Therefore, the additional overall landing time is resulted when flight $f - 1$ is reattached after flight f. Horizontal lines are also observed when the late path adjustment is positive, these flights are possibly related to the increment in wake separation after the swap in landing order. Then on the negative side of the y-axis (i.e., the area highlighted in light green), the swap starts to be potentially beneficial if the late path adjustment is over 92 seconds. The swap does not guarantee benefit even when flight f has sufficient late path adjustment as some original schedules are already in the optimal state.

In Fig. 17(c), we plot the swap benefit against the late path adjustment of flight $f + 1$. Compared to Fig. 17(b), the points in Fig. 17(c) are scattered which indicates that the late path adjustment of flight $f + 1$ is a less decisive factor in this swap. In Fig. 17(c), we still observe the horizontal lines in patterns (y-axis at around 100 seconds) that are similar to those in Fig. 17(b), but they extend beyond the positive x-axis which indicates that the late path adjustment of flight $f + 1$ is irrelevant in these swaps as the flight f has negative late path adjustment and cannot advance in landing time. Lower horizontal lines are also observed at heights similar to those in Fig. 17(b), these lines are the result of additional wake separation after the swap. When the late path adjustment of flight $f + 1$ is positive, the additional wake separation can be compensated and resulted in a diagonal line on the plot. We observe that the portion of flights benefited from the swap increase as the late path adjustment of flight $f + 1$ increases over 0 seconds.

In order to benefit from this arrival sequence swapping, the inefficiency has to be identified during operation, ideally as the flight enters the TMA. Therefore, it would be beneficial if the identification of this phenomenon can be done with predictable factors. Combining the two observations In Figs. 17(b) and 17(c), we notice that the magnitude of change in total landing time depends on the amount of late path adjustment of flight f and flight $f + 1$ as well as the overall change in required separation. The change in required separation is predictable while the individual late path adjustment is also available to a certain accuracy in the existing air traffic management tools. Illustrated in Fig. 17(d), using the aforementioned factors, we are able to rule out 70% of the flights (points in blue are more probable to be benefited).

IV. Conclusion

In this paper, we examined the separation deviation, the associated impact to the arrival efficiency, and its causes. We developed systematic identification methods to characterize inefficient arrival separation and back propagation effect using ADS-B flight trajectory feature extraction. Our identification of inefficient arrival separation associated the separation deviation with the use of TFGS. Results and findings from these analyses can guide the air traffic management authority to mitigate the inefficiencies by reevaluating the use of TFGS. Our identification of the back propagation effect explored the external effect of the inefficient arrival separation on other arrival flights. The identification attributed the late path adjustment of the follower flights to the inefficient separation of the preceding. These inefficiencies are

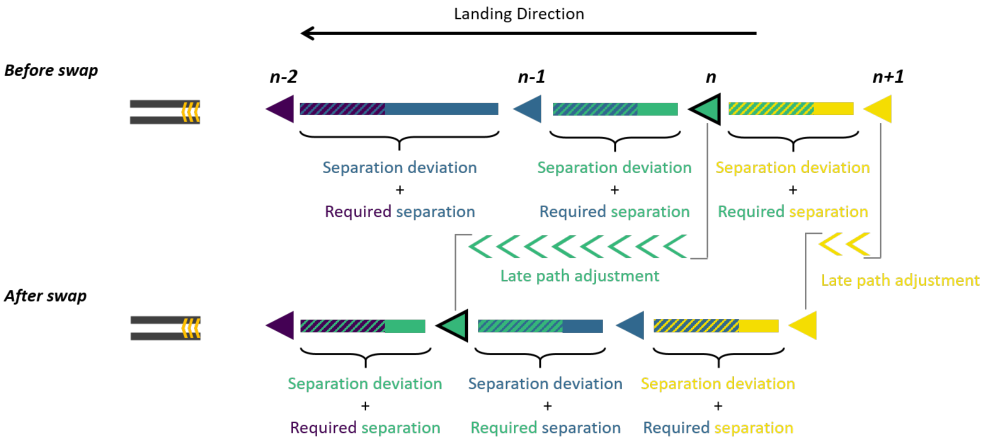
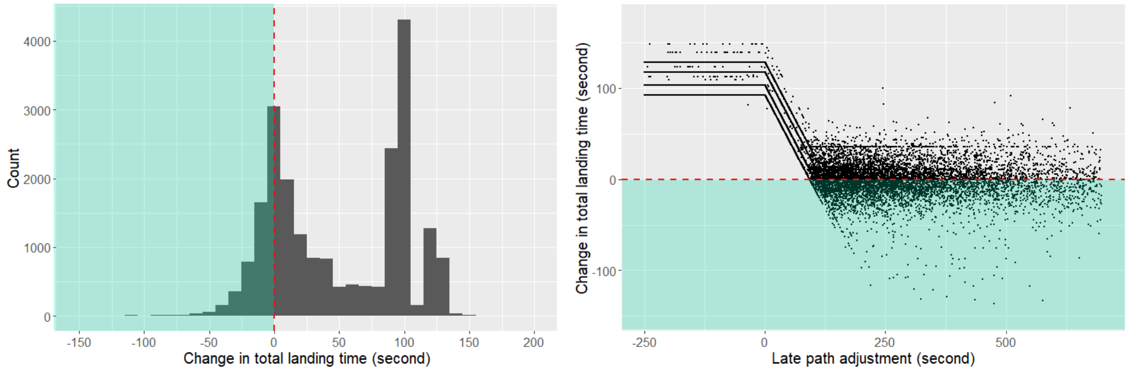
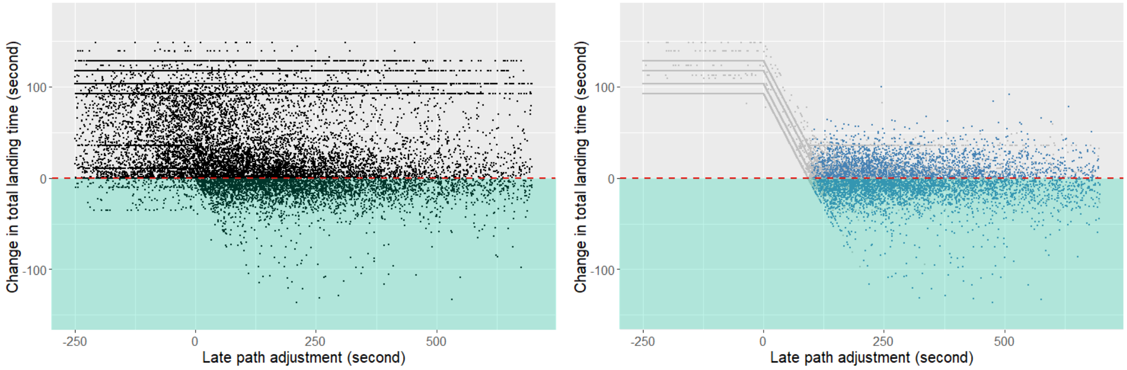


Fig. 16 Illustration of the arrival sequence swap with consideration of separation deviation and late path adjustment.



(a) Distribution of the change in total landing time after landing order swap (smaller is better).

(b) Flight f's late path adjustment vs change in total landing time.



(c) Flight $f + 1$'s late path adjustment vs change in total landing time.

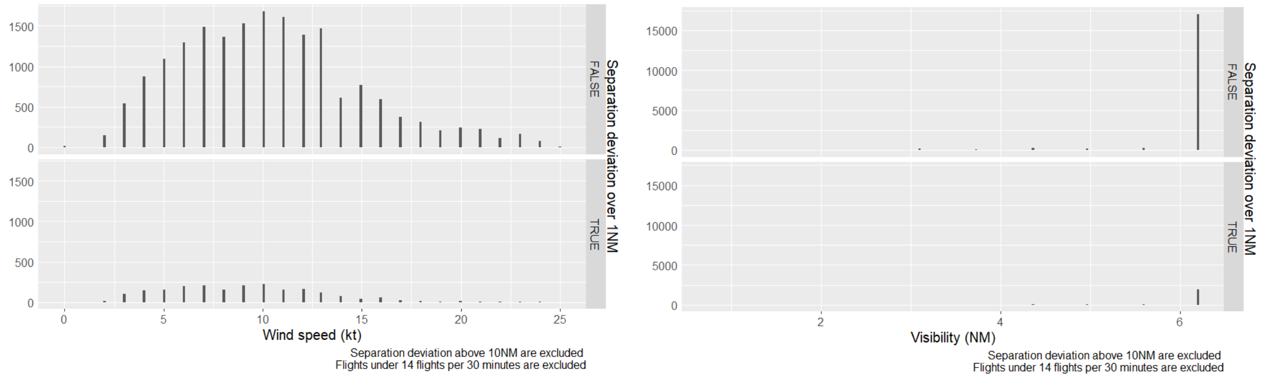
(d) Potential swaps selected with predictable factors.

Fig. 17 The benefit of landing order swap. Beneficial region are highlighted in light green

undermining the capacity and operation efficiency of the arrival system, of which our study provided quantitative evidences of the full extent of inefficiencies in separation deviation.

We evaluated the TMA arrival separation efficiency of Hong Kong International Airport. The analysis revealed that the amount of arrival flights with characteristics of inefficient separation can be substantial in some occasions (more than 10% of the daily arrival flights). We further examined the identified inefficiencies, the proposed potential causes, as well as the mitigation strategies. The back propagation analysis revealed that the inefficient separation can have extensive negative effect on the arrival traffic flow (up to more than 25% of the daily arrival flights). The new trajectory features discussed in our study can be applied into other air traffic operation efficiency investigations. Further studies can refine the accuracy of the identification and categorize the source of inefficiency for countermeasure development. Our study revealed that if the inefficiencies are mitigated, the air traffic system can have 2 to 3% capacity improvement on average. For flights that are affected by the back propagation, the potential arrival transit time reduction is up to 15%. This approach can serve as a bridging solution that does not require substantial investment and changes in the existing system. At this stage, our work is focused primarily on the post operation inefficiency identification, future study can explore the possibility of predicting the air traffic inefficiencies during live operations.

A. Appendix



Separation deviation above 10NM are excluded
Flights under 14 flights per 30 minutes are excluded

(a) Wind distribution

Separation deviation above 10NM are excluded
Flights under 14 flights per 30 minutes are excluded

(b) Visibility distribution

Fig. 18 The distributions of wind and visibility have no noticeable difference under different separation deviation conditions

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References

[1] Itoh, E., and Mitici, M., "Evaluating the impact of new aircraft separation minima on available airspace capacity and arrival time delay," *The Aeronautical Journal*, Vol. 124, No. 1274, 2020, pp. 447–471.

[2] Credeur, L., "Basic analysis of terminal operation benefits resulting from reduced vortex separation minima," Tech. rep., 1977.

[3] Geest, P. V. D., and Speijker, L., "Reduced wake turbulence separation at Schiphol airport CREDOS View project Wake-vortex Impact Severity Assessment View project," , 01 2014.

[4] Andrews, J., and Robinso, J., "Radar-based analysis of the efficiency of runway use," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, 2001, p. 4359.

[5] O'Connor, C. J., and Rutishauser, D. K., "Enhanced airport capacity through safe, dynamic reductions in aircraft separation: NASA's Aircraft Vortex Spacing System (AVOSS)," Tech. rep., 2001.

[6] Rooseleer, F., and Treve, V., ""RECAT-EU" European Wake Turbulence Categorisation and Separation Minima on Approach and Departure," , 2018.

[7] Ivanescu, D., Shaw, C., Tamvaclis, C., and Kettunen, T., "Models of air traffic merging techniques: evaluating performance of point merge," *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO) and Aircraft Noise and Emissions Reduction Symposium (ANERS)*, 2009, p. 7013.

[8] Boursier, L., Favennec, B., Hoffman, E., Rognin, L., Vergne, F., and Zeghal, K., "Combining sequencing tool and spacing instructions to enhance the management of arrival flows of aircraft," *AIAA 5th ATIO and16th Lighter-Than-Air Sys Tech. and Balloon Systems Conferences*, 2005, p. 7302.

[9] Hardell, H., Lemetti, A., Polishchuk, T., Smetanová, L., and Zeghal, K., "Towards a Comprehensive Characterization of the Arrival Operations in the Terminal Area," *11th SESAR Innovation Days*, 2021.

[10] Sprong, K. R., Haltli, B. M., DeArmon, J. S., Bradley, S., et al., "Improving flight efficiency through terminal area RNAV," *6th USA/Europe Air Traffic Management R&D Seminar*, 2005.

[11] Wing, D., Prevot, T., Morey, S., Lewis, T., Martin, L., Johnson, S., Cabrall, C., Como, S., Homola, J., and Sheth-Chandra, M., "Pilot and controller evaluations of separation function allocation in air traffic management," *USA/Europe Air Traffic Management Research and Development Seminar (ATM2013)*, 2013.

[12] Scharl, J., Berge, M. E., Haraldsdottir, A., and Schoemig, E. G., "A Near-Term Arrival Management Operational Concept and Preliminary Considerations," IEEE, Oct 2006, pp. 1–10. https://doi.org/10.1109/DASC.2006.313665, URL https://ieeexplore.ieee.org/document/4106252.

[13] Herrema, F. F., Treve, V., and Curran, R., "Typical additional spacing-buffer to apply at 4DME for delivering separation minima," *2015 IEEE/AIAA 34th Digital Avionics Systems Conference (DASC)*, IEEE, 2015, pp. 1F1–8.

[14] Szurgyi, S., Shresta, S., Neskovic, D., DeArmon, J., and Williams, S., "Analysis of observed aircraft-to-aircraft separations," *2008 Integrated Communications, Navigation and Surveillance Conference*, IEEE, 2008, pp. 1–11.

[15] Spinoso, L., Coville, G., and Roberts, C., "Analysis of the excess Inter-Arrival Time distribution," *2014 Integrated Communications, Navigation and Surveillance Conference (ICNS) Conference Proceedings*, IEEE, 2014, pp. A3–15.

[16] Bell, A., Enginuity, S., Beach, V., and Virginia, "Developing standards for time-based sequencing separation of aircraft," , -04 2012. https://doi.org/10.1109/icnsurv.2012.6218415.

[17] Dai, L., Liu, Y., and Hansen, M., "Modeling go-around occurrence using principal component logistic regression," *Transportation Research Part C: Emerging Technologies*, Vol. 129, 2021, p. 103262.

[18] Jou, R.-C., Kuo, C.-W., and Tang, M.-L., "A study of job stress and turnover tendency among air traffic controllers: The mediating effects of job satisfaction," *Transportation research part E: logistics and transportation review*, Vol. 57, 2013, pp. 95–104.

[19] Dancila, R., Botez, R., and Ford, S., "Fuel burn and emissions evaluation for a missed approach procedure performed by a B737-400," *The Aeronautical Journal*, Vol. 118, No. 1209, 2014, pp. 1329–1348.

[20] Gu, Y., Zhang, J., Zhou, M., and Wang, B., "Data-Driven Analysis of Final Separation Between Successive Landing Aircraft," *Transportation Research Record*, 2022, p. 03611981221082559.

[21] van Baren, G., Chalon-Morgan, C., and Treve, V., "The current practice of separation delivery at major European airports," *11th USA/Europe Air Traffic Management RD Seminar, Lisbon, Portugal*, 2015.

[22] Christien, R., Hoffman, E., and Zeghal, K., "Spacing and pressure to characterise arrival sequencing," *13th ATM Seminar*, 2019.

[23] Ren, L., and Clarke, J.-P. B., "Separation analysis methodology for designing area navigation arrival procedures," *Journal of Guidance, Control, and Dynamics*, Vol. 30, No. 5, 2007, pp. 1319–1330.

[24] Hong Kong Legislative Council Secretariat, "Development of the Hong Kong International airport," , 2015.

[25] Lui, G., Liem, R., and Hon, K., "Towards understanding the impact of convective weather on aircraft arrival traffic at the Hong Kong International Airport," *IOP Conference Series: Earth and Environmental Science*, Vol. 569, IOP Publishing, 2020, p. 012067.

[26] Zelinski, S. J., "Benefits of precision scheduling and spacing for arrival operations," *Journal of aircraft*, Vol. 50, No. 6, 2013, pp. 1923–1932.

[27] Ng, K. K., Chan, F. T., Qin, Y., and Xu, G., "The impacts of longitudinal separation, efficiency loss, and cruise speed adjustment in robust terminal traffic flow problem under uncertainty," *Transportation Letters*, 2022, pp. 1–24.

[28] Ng, K., Lee, C. K., Chan, F. T., Chen, C.-H., and Qin, Y., "A two-stage robust optimisation for terminal traffic flow problem," *Applied Soft Computing*, Vol. 89, 2020, p. 106048.

[29] Jun, L. Z., Alam, S., Dhief, I., and Schultz, M., "Towards a greener Extended-Arrival Manager in air traffic control: A heuristic approach for dynamic speed control using machine-learned delay prediction model," *Journal of Air Transport Management*, Vol. 103, 2022, p. 102250.

[30] Delgado, L., and Prats, X., "En route speed reduction concept for absorbing air traffic flow management delays," *Journal of Aircraft*, Vol. 49, No. 1, 2012, pp. 214–224.

[31] Franco, A., Rivas, D., and Valenzuela, A., "Minimum-fuel cruise at constant altitude with fixed arrival time," *Journal of guidance, control, and dynamics*, Vol. 33, No. 1, 2010, pp. 280–285.

[32] Drinkwater III, F. J., and Cooper, G. E., "A flight evaluation of the factors which influence the selection of landing approach speeds," Tech. rep., 1958.

[33] Barmore, B., "Airborne precision spacing: A trajectory-based aprroach to improve terminal area operations," *2006 ieee/aiaa 25TH Digital Avionics Systems Conference*, IEEE, 2006, pp. 1–12.

[34] Itoh, E., Everdij, M., Bakker, B., and Blom, H., "Speed control for airborne separation assistance in continuous descent arrivals," *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO) and Aircraft Noise and Emissions Reduction Symposium (ANERS)*, 2009, p. 6909.

[35] Balakrishnan, H., and Chandran, B. G., "Algorithms for scheduling runway operations under constrained position shifting," *Operations Research*, Vol. 58, No. 6, 2010, pp. 1650–1665.

[36] Rodríguez-Díaz, A., Adenso-Díaz, B., and González-Torre, P. L., "Minimizing deviation from scheduled times in a single mixed-operation runway," *Computers amp; operations research*, Vol. 78, 2017, pp. 193–202. https://doi.org/10.1016/j.cor.2016.09.014, URL https://dx.doi.org/10.1016/j.cor.2016.09.014.