

# [EN-106] Runway Capacity Estimation for Haneda Airport with 4<sup>th</sup> Runway (EIWAC 2010)

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**Abstract:** The purpose of this paper is primarily to develop an analytical model for estimating runway capacity of Haneda airport in Tokyo which will have new 4th runway in late 2010. Haneda airport will have two set of open-parallel runways with crossing layout (16/34 L/R, 04/22 L/R). Consequently, the departure and arrival traffics will operate dependently with higher complexity than current condition. By using the developed model, we analyzed the capacity of Haneda airport for random sequencing. We also analyzed the impact of the sequencing of the departure/arrival aircrafts considering wake turbulence category by using more heuristic model which consider the feasibility of arrival spacing on final approach in practice. From the analyses, we clarify the necessary constraints on aircraft sequencing and spacing for attaining the runway capacity planned by the government and for expanding the capacity.

**Keywords:** Runway capacity estimation, Haneda airport, Tactical sequencing

## 1. INTRODUCTION

Airport capacity in Tokyo metropolitan area has been always insufficient, especially in HANEDA airport (HND) where the majority of domestic air passenger in Japan (65%) concentrates, leading to extraordinarily large average aircraft size in HND (60-70% of the aircrafts in HND are "Heavy" aircraft in terms of wake turbulence category). HND will open new 4th runway in late October 2010 increasing the runway capacity from around 300 thousand movements/year to 410 thousand. After this capacity expansion, some portion of slots will be open to international scheduled flights though currently all the slots are basically for domestic flights. After this expansion, however, the capacity in the long run or peak-hour capacity could be still insufficient due to the continuous increase of international demand like inside Asia and the market changes such as higher frequency operation and denser network with smaller-sized aircrafts including Regional Jet. Therefore, it is important to study the possibility of runway capacity expansion after the HND expansion in 2010. The purpose of this paper is primarily to develop an analytical model for estimating runway capacity for HND which has multiple interdependent crossing runways, and also to analyze the impact of the sequencing of the departure/arrival aircrafts considering wake turbulence category with the developed model.

## 2. RUNWAY OPERATION IN HANEDA AIRPORT

In HND, two of three runways are currently operating simultaneously, but independently, and one is only for landing while the other is only for departure (Segregated-mode). The departure/arrival airways of HND

at low altitude are limited to Tokyo-bay area due to the noise problem (see Fig.1).

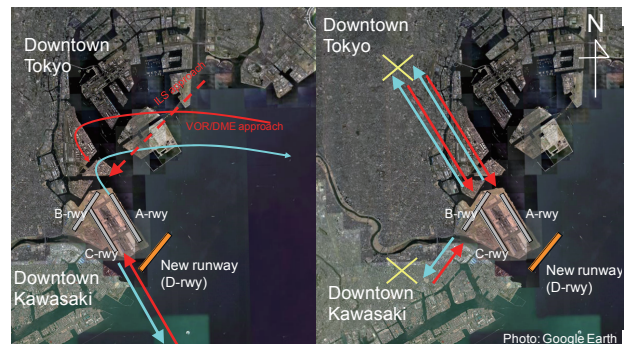


Figure.1 Current runway operation (left) and route restriction due to aircraft noise problem (right)

After the expansion, Japanese Civil Aviation Bureau (JCAB) has planned to operate 3 or 4 runways simultaneously and the airways will be still limited to bay area (Fig 2).

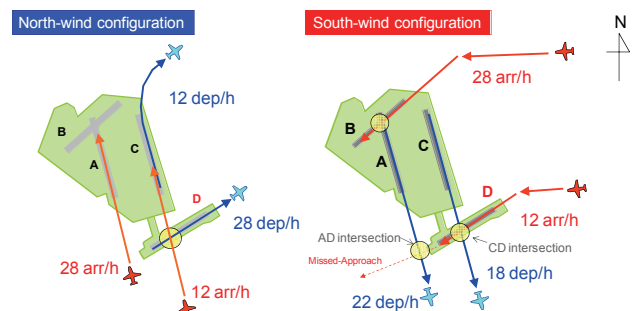


Figure.2 Runway operation and runway capacity per hour of HND with 4th runway (D-runway) (JCAB Plan)

Each runway will be dedicated to the aircrafts which fly to/from a certain direction (like to/from north or to/from south) in order to avoid conflict of aircrafts at the narrow terminal airspace in Tokyo. Furthermore, world-first simultaneous LDA (Localizer-Type Directional Aids) Approach will be adopted for simultaneous offset approach to parallel runways (south-wind configuration). By conducting real-time ATC simulation where actual air traffic controller joined, JCAB has concluded that runway capacity of HND with 4th runway is 40 landings and 40 take-offs /hour under the above-mentioned conditions.

### 3. DEVELOPMENT OF RUNWAY CAPACITY ESTIMATION MODEL FOR HANEDA AIRPORT WITH 4<sup>th</sup> RUNWAY

#### 3.1 Capacity Estimation Modeling for Multiple Crossing Runways

##### 3.1.1 Basic Concept

The existing analytical runway capacity models are based on calculating of expected value of inter-event time between the leading and trailing aircraft. This kind of calculation is easy for single crossing runways (one intersection). In this study, the capacity model for multiple crossing runways is developed by combining the capacity models for the two sets of single crossing runways (C-D runway and A-D runway). Therefore, we first consider the inter-event time of all sequences (we call this time ‘‘System Occupancy Time (OT)’’) for two set of single crossing runways separately. And then we consider the method of combining the capacity models for the two sets of crossing runways with some assumptions. Finally the capacity for multiple crossing runways is calculated based on Monte-Carlo Simulation.

##### 3.1.2 Occupancy Time for Single Crossing Runways

As is shown in Fig.2, the operation in the south-wind configuration is more complicated than in the north-wind configuration, where the arrival route to D-runway is intersecting with departure routes from both A- and C-runways (We call these two intersecting points ‘‘AC intersection’’ and ‘‘CD intersection’’ respectively: see Fig. 2). In this paper, therefore, we describe the capacity only in the south-wind configuration due to the limited space of the paper.

As it is often the case with runway capacity models, single occupancy rule is adopted for single crossing runways. However, in the case of HND, how to interpret the occupancy rule is different from the usual cases because the runways in HND do not physically intersect. We assume that only one aircraft occupies the system at the same time, and its ‘‘occupancy right’’ transfers to the following aircraft at a certain point. For example, in the case of the system of C-runway and D-runway (CD system), the point is ‘‘When Departure aircraft from C-runway crosses CD intersection’’ if the arrival to D-runway (Arr\_D) follows the departure from C-runway (Dep\_C) or ‘‘When assuring the landing of arrival aircraft to D-runway’’ if Dep\_C follows Arr\_D. In other sequences cases, such as two consecutive Dep\_C and two consecutive Arr\_D, we use the existing method. With this concept, we calculate the occupancy time

of the system (OT) of the middle aircraft among three consecutive aircrafts, which varies depending on the wake turbulence category and flight type (arrival/departure) of its preceding and succeeding aircrafts.

Let  $T_{ijk}$  be the OT of aircraft  $j$  between the preceding aircraft  $i$  and the succeeding aircraft  $k$  ( $i, j, k=C$ (or A)-runway, D-runway) which includes some buffer time for computing runway capacity, and  $t_{ijk}$  be the actual time of occupying the system. Similar to the existing researchs<sup>[1)]</sup>, the basic assumption is

$$t_{ijk} \sim N(\bar{t}_{ijk}, \sigma^2). \tag{1}$$

where  $\sigma$  is the standard deviation of  $t_{ijk}$ .  $\bar{T}_{ijk}$  is set such that the ATC separation rule is violated with a small probability  $p_v$ . Then

$$T_{ijk} = \bar{t}_{ijk} + \sigma\Phi^{-1}(1 - p_v) \tag{2}$$

where  $\Phi^{-1}$  is the cumulative standard normal distribution function. In JCAB model,  $p_v$  is usually set to 0.005, and this study set the same value when observed data including the deviation  $\sigma$  is available. Otherwise, we calculated the OTs by using the safe-side parameters such as smaller flight speed among different type of aircrafts for converting minimum distance separation to the time separation.

Table 1 Basic Parameters and Assumptions for Capacity Estimation

[1] Aircraft	* Three categories, B777/B767/B737, for speed setting * Heavy : Medium = 0.7 : 0.3 (Wake turbulence category mix) (HND doesn't have ‘‘Light’’ aircraft)
[2] Aircraft Speed	[Departure] 160kt after airborne [Arrival] 180kt(9NM: from runway landing threshold), 160kt(5NM), 145kt/135kt/125kt (3NM, B777/B767/B737) [Missed approach] 160kt from SOC (start of climb) or 160kt from MAPt (missed approach point)
[3] Runway Occupancy Time (ROT)	[Consecutive Take-off] 95s (15s (response time) + 35s (Start rolling ~ airborne) + 45s (required time for radar separation from following take-off aircraft)) [Consecutive Landing] 115s (88s (average time from landing runway threshold to runway exit + buffer for its variance) + 27s (Additional buffer: 1NM flight time from runway threshold))
[4] ATC separation and the other parameters	[Separation between take-off and landing aircraft] (1) 2NM (3NM at 1minute after airborne), (2) 2 minutes after heavy aircraft (when departure and arrival route is crossing above runway: landing to D-runway after take-off from C-runway in HND) [Landing assurance time] 25s (The time duration after passing landing threshold required by Tower controller for assuring that landing aircraft is never going to go-around) [Impact of engine thrust from take-off aircraft] 15s is assumed for assuring that there is no impact of engine thrust from take-off aircraft on the other aircraft behind take-off aircraft (Take-off from A-runway before Landing to B-runway in south-wind configuration) [Landing clearance] Landing clearance should be issued before reaching 1NM from landing runway threshold.

In order to compare the model output with the capacity planned by JCAB, we basically used the existing parameters which are usually assumed in JCAB<sup>[5)]</sup> such as runway occupancy time and aircraft speed. However, since those parameters are mainly for a single runway, we had to consider additional parameter settings for multiple crossing runways based on Air Traffic Control Standard<sup>[6)]</sup> and the

local operational rules in HND etc. Table 1 shows the basic parameters and assumptions for computing OTs.

3.1.3 Examples of Occupancy Time (OT) for Single Crossing Runways: CD System

(i) OT of the case [Arr\_D->Dep\_C->Arr\_D]:  $T_{DCD}$   
 According to the concept of OT described in the previous section, the OT of the Dep\_C between Arr\_Ds,  $T_{DCD}$ , is the required time from take-off clearance to crossing CD intersection.  $T_{DCD}$  can be divided into three sections; (1) "take-off clearance" to "start of take-off rolling" (Response time): 15s", (2) "start of take-off rolling" to "airborne (assuming 1800m point)": 48s, and (3) "airborne" to "crossing CD intersection (2600m from airborne point)": 32s. Here, time (2) includes safety buffer considering the speed variance, and time (3) is calculated by assuming the climbing speed of 160kt (minimum speed).

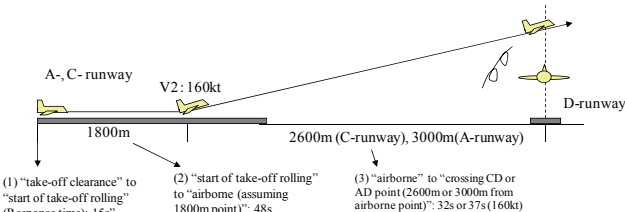


Figure 3 Required times for departure aircraft from A- and C-runway

(ii) OT of the case [Dep\_C->Arr\_D-> Dep\_C]:  $T_{CDC}$   
 $T_{CDC}$  differs depending on the wake turbulence category of preceding Dep\_C (Heavy (H) or Medium (M)). If it is Heavy, 2-minute separation is required from the preceding Dep\_C's passing CD intersection until the succeeding Arr\_D's passing CD intersection (see Fig.4). This 2-minute can be converted to a certain distance by assuming approach speed, which differs among aircraft types. In practice, this distance will be used for the threshold that allows Tower controller to issue Take-off Clearance to Dep\_C prior to Arr\_D. If the threshold can be set to one distance value for easing Tower controller work, it is necessary to calculate the distance by the fastest approach speed. Therefore, based on the speed of B777, it becomes 4.1NM from runway landing threshold. On the other hand, the slowest approach speed (B737) should be used for calculating the OT to include the safety buffer for variety of approach speeds of different aircraft types. Then, the 4.1NM can be converted to 117s. As a result,  $T_{C(H)DC}$  becomes 142s by adding 25s as "Landing assurance time (see Table.1)" to 117s.

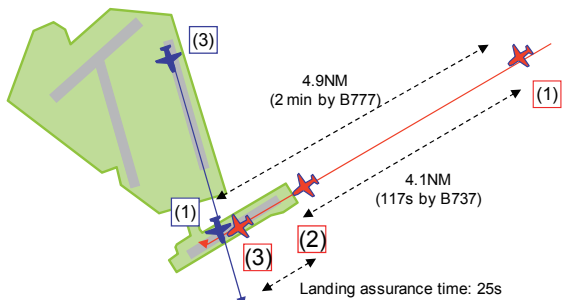


Figure.4 Image of occupancy time of arrival to D-runway after "Heavy" departure from C-runway

When the case preceding Dep\_C is Medium, the minimum

ATC separation becomes "Radar separation between take-off and landing aircraft, 2NM (see Table.1). In another word, the separation should be kept more than 2NM when two aircrafts are closest (when the triangle formed by the three points, the two aircrafts and the CD intersection, becomes isosceles triangle if the two aircrafts fly at the same speed) (see Fig.5). In this condition, Arr\_D (succeeding) should be further than 4.1NM from landing runway threshold when Dep\_C (preceding) crosses CD intersection. This 4.1NM can be converted to 47s (by speed of B737). Then,  $T_{C(M)DC}$  becomes 72s by adding 25s as "Landing assurance time" to 47s as well as  $T_{C(H)DC}$ .

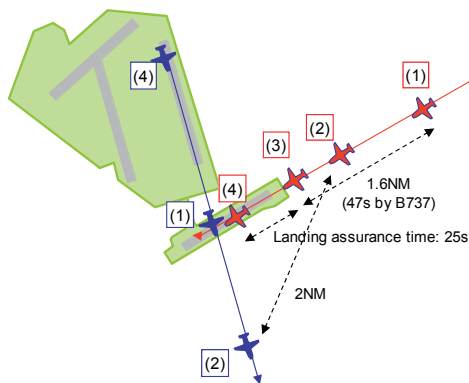


Figure.5 Image of occupancy time of arrival to D-runway after "Medium" departure from C-runway

If we assume the complete alternate operation of Dep\_C and Arr\_D, the hourly capacity of CD system,  $CAP_{CD}$ , can be calculated as follows:

$$CAP_{CD} = 2 \times 3600 / \sum_{i=H,M} S_i (T_{DCD} + T_{C,DC}) \quad (3)$$

$$\cong 33 (\text{movements} / \text{h})$$

where  $S_i$  is the share of Heavy and Medium aircraft (H:M=0.7:0.3)

Since Arr\_D operation would also depend on Dep A, the calculation of the runway capacity of total HND will be more complicated.

3.1.4 ATC Separation and Occupancy time (OT) of AD System

Basic concept of OT for AD system is essentially the same to that of CD system, but there is no wake turbulence separation between Dep\_A and Arr\_D according to the Japanese ATC standard (the flight route of Dep\_A and Arr\_D are not crossing above runway) and Tower controller must see the impact of engine thrust from Dep\_A on arrival aircraft to B-runway (Arr\_B).

3.1.5 Occupancy Time (OT) for the Other Cases

OTs for other combination of consecutive three aircrafts  $T_{ijk}$  are not described in detail, but the basic concept is the same. For example,  $T_{C(H)C(H)D}$  is the same as  $T_{DCD}$  mentioned above, and  $T_{DC(H)C(H)}$  is the same as wake turbulence separation for consecutive departure of Heavy aircraft (120s, and 95s in the Medium departure case) (see Table.1). In the case of consecutive arrival to D-runway, the OT is the required time



until vacating runway. For example, the  $T_{DD(M)D}$  is the same as Runway Occupancy Time of landing aircraft (115s) and  $T_{DD(H)D}$  is the same as wake turbulence separation for consecutive arrival of Heavy aircraft (120s).  $T_{C(H)DD}$  can be calculated by summing 117s (time of flying 4.1NM mentioned in (b)(ii)) and 88s (Runway Occupancy time: see Table.1). Fig.6 shows the OTs for all other combinations of three consecutive aircrafts in AD and CD systems calculated in similar ways. The number of the combinations becomes 64 in each system since we distinguished them based on two wake turbulence category (H or M).

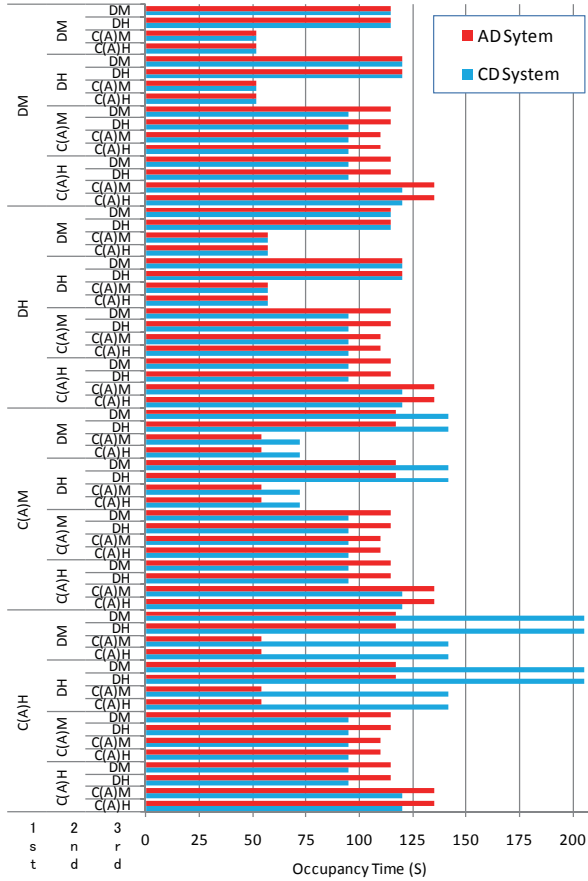


Figure.6 Occupancy time (OT) of the all combination of three consecutive aircrafts in AD and CD system (OT of the 2nd aircraft)

### 3.1.6 Capacity Estimation with Simultaneous Consideration of Both CD and AD System (three runways)

For calculating the total runway capacity in HND, we need to consider CD and AD system simultaneously since the two systems operate dependently through the arrival to D-runway (Arr\_D). Here, it is important to consider how to control the separation of consecutive Arr\_D efficiently to enable the take-off of Dep\_A and Dep\_C in the space of two consecutive Arr\_D with minimum loss. As shown in Table.2, OTs between CD and AD system are different even in the same sequence. Therefore, if the separation of consecutive Arr\_D is controlled optimally for Dep\_A based on the OT of AD system, Dep\_C may not necessarily be able to depart in that separation and vice versa. In these conditions, the capacity loss will be large in most of the cases, so we assumed that the number of departure from AD and CD system between consecutive Arr\_Ds are basically

the same for simplifying the calculation. Here, a problem of under-estimation of capacity might occur with this assumption. We discussed this problem in the latter section.

In order to calculate the capacity of these three runways with the above-mentioned assumption, we focus the number of departures between consecutive arrivals. From this point of view, the operation of the runway subsystems (CD or AD system) which consists of a dependant pair of a landing runway and a departure runway can be expressed as a mixture of the following operation sequence types:

Type of operation sequence	# of Dep	# of Arr	Occurrence Probability	Sum of OT
(Arr), Arr	0	1	$P_a$	$T(0)$
(Arr), Dep, Arr	1	1	$P_a \cdot P_d$	$T(1)$
(Arr), Dep, Dep, Arr	2	1	$P_a \cdot P_d^2$	$T(2)$
:	:	:	:	:
(Arr), Dep, ---, Dep, Arr	n	1	$P_a \cdot P_d^n$	$T(n)$

where Arr is arrival, Dep is departure, (Arr) is the last arrival of preceding sequence,  $P_a$  and  $P_d$  are the arrival and the departure probability respectively.

The sum of OT of each type of operation sequence  $T(n)$  consists of one or more occupancy times of the runway subsystem ( $T_{ijk}$ ). In the case of  $T(n)$  of CD system, ( $T_{CD}(n)$ ) is expressed as follows;

$$T_{CD}(n) = \begin{cases} T_{DDC} & (n=0) \\ T_{DCD} + T_{CDC} & (n=1) \\ T_{DCC} + (n-2)T_{CCC} + T_{CCD} + T_{CDC} & (n=3, \dots, \infty), \end{cases} \quad (4)$$

Note: For simplicity, we ignored the subscripts indicating wake turbulence category

where the aircraft after the last arrival of each sequence assumed to be departure. Because the types of operation sequence shown above are mutually exclusive and exhaustive, we can calculate the arrival and departure capacity of this runway subsystem (case of CD system) per hour as below;

$$CAP_{CD}(dep) = 3600 \left/ \left[ \frac{\sum_{n=0}^{\infty} T(n) \cdot P_a \cdot P_d^n}{\sum_{n=0}^{\infty} n \cdot P_a \cdot P_d^n} \right] \right. \quad (5)$$

$$CAP_{CD}(arr) = 3600 \left/ \left[ \frac{\sum_{n=0}^{\infty} T(n) \cdot P_a \cdot P_d^n}{\sum_{n=0}^{\infty} 1 \cdot P_a \cdot P_d^n} \right] \right. \quad (6)$$

Here, it is assumed that the every arrival intervals are optimized to the  $T(n)$  of this runway subsystem one by one, and that there are continuous demand for landing and departure, as is an usual assumption in calculating an ultimate capacity of runways.

Based on the assumption that the number of departure from AD and CD system between consecutive Arr\_D are the same, the inter-arrival time of Arr\_D must be adjusted to the larger value among  $T_{CD}(n)$  and  $T_{AD}(n)$ . As a result, the capacity of the runway system which is a combination of CD and AD subsystems (a pair of independent departure

runways and a landing runway dependent to the departure runways),  $CAP_{CD+AD}$ , is expressed as follows;

$$CAP_{CD+AD}(dep) = 3600 \left[ \frac{\sum_{n=0}^{\infty} \max [T_{CD}(n), T_{AD}(n)] \cdot P_a \cdot P_d^n}{\sum_{n=0}^{\infty} 2n \cdot P_a \cdot P_d^n} \right] \quad (7)$$

$$CAP_{CD+AD}(arr) = 3600 \left[ \frac{\sum_{n=0}^{\infty} \max [T_{CD}(n), T_{AD}(n)] \cdot P_a \cdot P_d^n}{\sum_{n=0}^{\infty} 1 \cdot P_a \cdot P_d^n} \right] \quad (8)$$

where  $T_{CD}(n)$  and  $T_{AD}(n)$  are the sum of OT of the type of operation sequences of each runway subsystem.

**3.2 Result of the Capacity Estimation by Monte Carlo Simulation for Random Sequencing**

In order to analytically compute  $CAP_{CD+AD}$ , we need to compute infinite number of combination of  $T_{CD}(n)$  and  $T_{AD}(n)$ . Therefore, we conducted a numerical simulation (Monte-Carlo Simulation) to get approximate solution of  $CAP_{CD+AD}$ , where a total of 10,000 aircrafts are served by the three runways. The sequence of arrival/departure and the category of each aircraft were determined randomly based on the arrival/departure ratio and Heavy/Medium ratio (H:M=0.7:0.3) to get the capacity curve the simulation was conducted twenty times by changing the arrival/departure ratio. Then, we can obtain the approximate solution of the capacity by expected value of the required time for serving one aircraft that can be obtained by computing the cumulative larger value among  $T_{CD}(n)$  and  $T_{AD}(n)$  for all of the aircraft sequences generated.

The result of the simulated capacity curve of arrival and departure is shown in Fig.7. As arrival ratio increases, departure capacity decreases at higher rate than the arrival increases, because the arrival to D-runway blocks departures from two runways (C and A runway). If we look at the planned capacity by JCAB (40 arrivals + 40 departures: even ratio of arrival/departure), the capacity is almost the same as the simulated capacity.

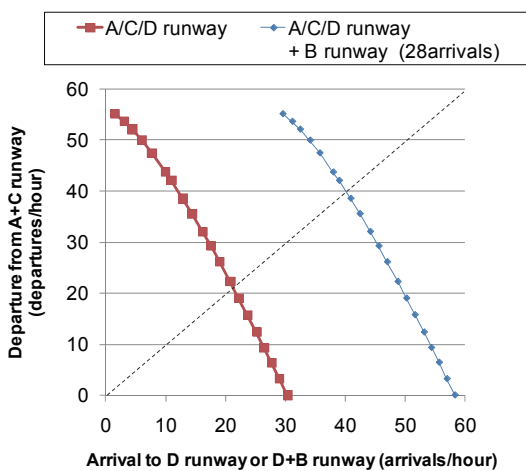


Figure.7 Capacity estimation result for multiple crossing runways (blue line indicates the total capacity including 28 arrivals/h to B-runway: assuming independent operation)

Here, the capacity tends to under-estimate when departure ratio increases. This is because, even if the time gap between  $T_{CD}(n)$  and  $T_{AD}(n)$  is larger than the  $T_{ijk}$  it can't be used for additional departure due to the assumption that the number of departures from A- and C- runways for a given arrival interval are fixed to be the same. The time gap becomes larger as departure ratio increase because of high probability of continuing departures. With rough estimation where minimum time gap to be used for additional departure assumed to be 95 seconds, it turned out that if arrival ratio is smaller than around 0.35, the total capacity loss of departure is less than 1% of the simulated capacity. Such a small loss can be ignored in practice, but the loss could be as high as 10% when arrival ratio is very small (0.05). Usually the arrival/departure ratio is almost even, if we see the congested airport where the slots are fully coordinated like HND. Therefore, the proposed capacity model can be adopted for such airports. However we must consider the way to solve this kind of under-estimation problem in future studies.

**3.3 Capacity Estimation for A-Priori Sequencing Considering Practical Arrival Spacing and the Impact of Sequencing Change on Capacity**

*3.3.1 A-Priori Sequencing Considering Practical Arrival Spacing*

When we look at the capacity estimation model for random sequencing mentioned above from the actual ATC operation point of view, the separation between consecutive Arr\_D in the final approach course must be controlled so flexibly by always thinking how many and what type (wake category) of departure aircraft will be released from A- and C-runways within the separation. In practice, the feasibility of such flexible controlling might not be high, at least in the current ATC technology condition. It is more practical to assume that "a priori sequencing of arrival and departure with fixed number of departure between consecutive Arr\_Ds or with fixed separation of consecutive Arr\_Ds" for capacity calculation. In this case, we assumed that the sequencing of arrival and departure is a priori based on the arrival/departure mix. In other word, the number of Dep\_C and Dep\_A between consecutive Arr\_Ds is assumed to be in a certain pattern. The simplest pattern is fixing that the number of Dep\_C and Dep\_A between consecutive Arr\_Ds to a single number (e.g. two departures from each runway). Furthermore, to make the separation control in final approach more feasible, we fixed the separation to the maximum distance among possible required separations. Even if the number of departure between consecutive Arr\_Ds is fixed to single number, the required separation between consecutive Arr\_Ds would be variable based on the aircraft type of Dep\_C and Dep\_A in terms of wake turbulence category. In the following analysis, we assumed this simplest and most feasible (easiest) operation approach for the impact of sequencing change on capacity.

*3.3.2 Analysis of the runway operation for the planned capacity by JCAB and the impact of sequencing*

As shown in Fig.2 (JCAB plan of HND capacity after expansion), Arr\_D, Dep\_C and Dep\_A are planned to serve 12 landings/hour, 22 departure/hour and 18 departure/hour respectively. Based on the planned capacity and the



assumption (fixed separation of consecutive Arr\_Ds), two departures from each of A- and C-runway between consecutive Arr\_D are required. With this operation assumption and OTs shown in Fig.6, we analyzed the runway operation for the capacity planned by JCAB.

The first case is for a mixture of aircraft types and the aircrafts served are “first-in, first-out” (FIFO). Fig.8(A) shows the runway operation and OTs in this case, and “CH” means Dep\_C of Heavy aircraft and “AM” means Dep\_A of Medium aircraft in the figure. Since FIFO is assumed for a mixture of aircraft types, the maximum arrival separation in D-runway 357s, that is in the case of two consecutive Heavy Dep\_Cs. If this maximum time 357s is fixed as separation interval, then the capacity of Arr\_D would be 10 landings/hour and that of both Dep\_C and Dep\_A would be 20 departures/hour, which are totally less than the capacity of JCAB plan.

The second case is analyzed when the aircrafts are served by optimized sequencing to some extent for minimizing large wake turbulence separation occurrence. As shown in Fig.6, the wake turbulence separation caused by Heavy Dep\_C followed by Arr\_D is relatively large. If the Dep\_C followed by Arr\_D is limited to Medium aircraft, the maximum arrival separation in D-runway can be reduced to 304s (the separation in the case of two consecutive Heavy Dep\_As). Even in this tactical sequencing the capacity is still little bit lower than that of JCAB plan in terms of the capacity of Arr\_D. However, planned capacity of JCAB can be attained by relaxing the fixed arrival separation, where one departure between two consecutive Arr\_Ds is accepted once in an hour (this is not, of course, the only case to attain JCAB plan). Fig.8(B) shows the image of this operation. In practice, it is not easy for controllers to always limit the departure followed by Arr\_D to Medium aircraft, especially in HND which have large number of Heavy aircrafts. However, to attain the JCAB planned capacity, it is enough to release two departures from C-runway once in

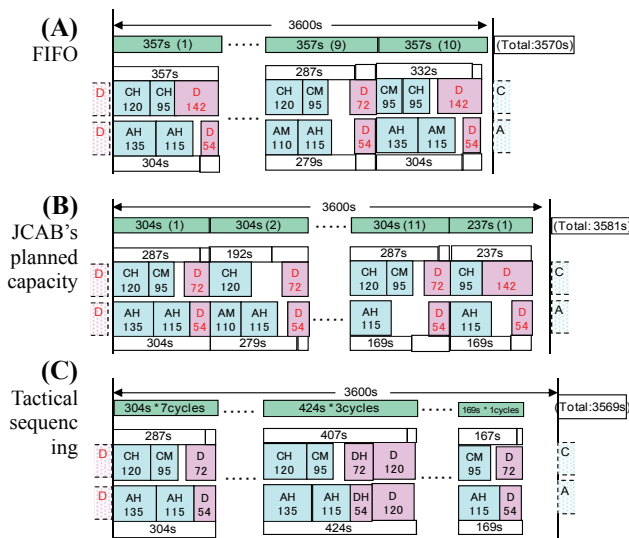


Figure.8 Image of runway operation and OTs (A) with fixed arrival separation and FIFO, (B) with tactical sequencing with some buffer slots for JCAB planned capacity, and (C) with tactical sequencing without buffer slots

Table.2 Summary of Three Cases of Operation	
<b>(A) FIFO + Fixed arrival separation</b> [Capacity: 78movements/h]	
Arr_D	Landing at around 6 minutes interval
Dep_A	Two departures between consecutive Arr_D (FIFO)
Dep_C	Two departures between consecutive Arr_D (FIFO)
Capacity of each runway (South-wind config.)	
<b>(B) Tactical sequencing with some buffer slots for JCAB planned capacity</b> [Capacity:80movements/h]	
Arr_D	Landing at around 5 minutes interval (in one cycle, landing at around 4.5 minutes interval)
Dep_A	Basically, two departures between consecutive Arr_D (FIFO) (in two cycles, only one departure is allowed)
Dep_C	Two departures between consecutive Arr_D (departure followed by Arr_D is limited to Medium aircraft) (in six cycles, only one departure is allowed)
Capacity of each runway (South-wind config.)	
<b>(C) Tactical sequencing without buffer slots</b> [Capacity:84movements/h]	
Arr_D	Landing at around 5 minutes interval (landing at around 3 minutes interval in one cycle, and two consecutive landings in three cycles)
Dep_A	Basically, two departures between consecutive Arr_D (FIFO)
Dep_C	Two departures between consecutive Arr_D (departure followed by Arr_D is limited to Medium aircraft)
Capacity of each runway (South-wind config.)	

two cycles (one cycle means, for example, “Dep\_C->Dep\_C->Arr\_D”). This means that there are enough buffering time that allow controllers to release only one heavy aircraft if they do not have stand-by Medium aircrafts beside a departure runway.

If we can fully release the departures from C- and A-runway based on the tactical sequencing shown in Fig.8(B) and by allowing some consecutive landings to D-runway, the maximum capacity becomes 84 movements/hour (Fig. 8(C)).

#### 4. CONCLUSIONS

In this study, we primarily developed an analytical model for estimating runway capacity for the airports which has multiple crossing runways like HND after the expansion. The unique point of this modeling is that the interaction among three crossing runways is simultaneously considered and the practical capacity curve of the runway system in changing arrival/departure mix is computed by Monte-Carlo Simulation. We also analyzed the impact of the sequencing of the departure/arrival aircrafts considering wake turbulence category by using more heuristic model which takes into account practical feasibility of arrival spacing on final approach. The analysis results show that the runway capacity of HND after expansion will be less than JCAB planned capacity if controlling arrival and departure aircrafts is by FIFO and fixed arrival separation (this is close to current operation in HND). For attaining the JCAB planned capacity, it may be necessary to do tactical sequencing to minimize large wake turbulence separation occurrence to some extent. If we can fully release the departures from C- and A-runways by the tactical sequencing, the maximum capacity becomes 84 movements/hour. Currently, two runways are operating independently and in segregated mode. After the expansion, by adding 4<sup>th</sup> runway, HND will have multiple converging traffics of arrivals and departures; consequently the runways will operate in a highly dependent way. After the expansion of HND, the sequencing strategy of arrival and departure aircrafts will become much more important for enhancing the runway capacity, as is shown in the analysis.

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