Studies of capacity estimation of the airport with two parallel runways

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ABSTRACT

The analytical capacity models of an airport with two runways system are developed in this paper and the theoretical capacity curves yielded by this model are analysed. The statistic airport capacity estimation methodology based on historical data is introduced as well. Both analytical models and statistic strategy are applied to estimate the capacity of the two runways system of a typical airport. Two sets of airport capacity curves obtained in different ways are compared and analysed. The result of the analysis indicates that the mathematical model works effectively in a fairly accurate way in the estimation of airport capacity.

NOMENCLATURE

$[A_{ij}^{k_{ij}}]_{n\times n}$	runway idle time matrix with its expression shown in Equation (9)
$AASR(ij)$	time separation requirement between arrival aircraft i (leading) and j (trailing)
$AROR(i)$	runway occupancy time requirement by arrival aircraft of type i
$C\ (DA)$	arrival/departure capacity
$C\ (TM)$	capacity of the two runways system in two mixed mode operations
$C_A\ (AA)$	arrival capacity
$C_A\ (DA)$	arrival capacity of the runway employing mixed mode operations
$C_D\ (DA)$	departure capacity of the runway employing mixed mode operations
$C_D\ (DD)$	departure capacity
$[Delay]_{n\times n}$	runway delay time matrix
$DASR(j)$	time separation requirement between departure aircraft i and arrival aircraft j
$DDSR(ij)$	time separation requirement between departure aircraft i (leading) and j (trailing)
$DROR(i)$	runway occupancy time requirement by departure aircraft of type i
$n_{ij\max}$	maximum number of departure aircraft inserted between two consecutive landing aircraft
P_i, P_j, P_g	respectively the proportions of aircraft of type i, j and g in traffic mix (see aircraft i, j and g in Fig. 2)
P_{ij}	probability of the case when the leading aircraft is of type i, and the trailing aircraft is of type j
PRI	departure/arrival priority index of the runway
$T_{ij}(AA)$	time difference between arrival aircraft i (leading) and arrival aircraft j (trailing) to pass the runway threshold
$T_{ij}(DD)$	time difference between departure aircraft i (leading) and aircraft j (trailing) to commence departure

1.0 INTRODUCTION

The airport capacity estimation is a key part of air traffic management technology. To avoid or reduce flight delays while maintaining adequate degree of safety, capacity estimation of the airport and other national airspace components is playing an irreplaceable role. Relevant studies have shown that the runway

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system, as a likely 'bottleneck' of the air traffic, often governs the capacity of the whole airport[1-3]. Most of the previous studies of airport capacity have been generally focused on the airport with one runway[1,4], while with the significant growth of air traffic, more and more airports are operating with multiple runways system[5,6]. In the work presented here, the capacity of the two parallel runways of a typical international airport is analysed, and the theoretical result is verified by being compared with the airport historical performance data.

2.0 MATHEMATICAL MODELS FOR AIRPORT RUNWAY CAPACITY ESTIMATION

The mathematical models developed for computing the capacity of an airport are generally based on two concepts of the capacity[4]. Both Concepts consider an airport as a service system where customers (like aircraft, passengers and freight shipments) have requested and received service in a given period of time under given conditions. The first concept of capacity is called 'ultimate' or 'saturation' capacity, and the other concept is called 'practical' capacity.

Ultimate capacity of an airport can be expressed by the maximum number of entities (aircraft, passengers, bags, and freight shipments) that can be served in a given period under conditions of constant demand for service. Practical capacity of an airport can be defined through the maximum number of entities that can be served in a given period of time under condition when the average delay imposed on each entity doesn't exceed a level prescribed in advance.

Two kinds of air capacity mathematical models have been widely used by airports and air traffic control authorities: analytical models and simulation models[6]. Analytical models are basically employed during the preliminary phase of the capacity evaluation, featuring simplicity and convenience of their implementation while generating less accurate but appropriate results. The most common analytical models are respectively: time-space analytical models and queuing models. Simulation models are usually good for detailed assessment of existing facilities, and distinguished from analytical model by the precise results with microscopic nature, complexity of development, and the high cost of execution. Generally speaking, simulation models can be classified into the following three categories: Monte Carlo simulation models, continuous simulation models, and discrete-event simulation models.

In this work, time-space analytical models will be developed to estimate the capacity of the two parallel runways system of an airport.

3.0 CAPACITY MODEL OF THE SINGLE RUNWAY SYSTEM

All aircraft operating in the considered airport are classified into n groups based on the wake vortices they generate. Define matrix $P = [p_{ij}]_{n\times n}$, while p_{ij} represents the probability of the case when the leading aircraft is of type i, and the trailing aircraft is of type j. Other relevant important variables are defined as follows[9].

$AROR(i)$: Runway occupancy time requirement by arrival aircraft of type i

$AASR(ij)$: Time separation requirement between arrival aircraft i (leading) and j (trailing)

$DROR(i)$: Runway occupancy time requirement by departure aircraft of type i

$DDSR(ij)$: Time separation requirement between departure aircraft i (leading) and j (trailing)

$DASR(j)$: Time separation requirement between departure aircraft i and landing aircraft j

$T_{ij}(AA)$ Time difference between arrival aircraft i (leading) and arrival aircraft j (trailing) to pass the runway threshold

$T_{ij}(DD)$ Time difference between departure aircraft i (leading) and aircraft j (trailing) to commence departure

The operation scenario of the runway will be one of the followings[9]: AA (Arrival_Arrival), DD (Departure_Departure), DA (Departure_Arrival or Mixed Mode Operations). Other variables and their definitions used in the analytical model are available in Refs 4,7,8 and 9.

3.1 Arrival capacity C_A (*AA*)

$$T_{ij}(AA) = \max(AROR(i), AASR(ij)) \quad \ldots (1)$$

The expected value of T_{ij}(AA) is expressed as below;

$$T(AA) = E[T_{ij}(AA)] = \sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij}T_{ij}(AA) \quad \ldots (2)$$

$$C_A(AA) = 1/T(AA) \quad \ldots (3)$$

3.2 Departure capacity C_D (*DD*)

$$T_{ij}(DD) = \max(DROR(i), DDSR(ij)) \quad \ldots (4)$$

The expected value of T_{ij}(DD) is expressed as below;

$$T(DD) = E[T_{ij}(DD)] = \sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij}T_{ij}(DD) \quad \ldots (5)$$

$$C_D(DD) = 1/T(DD) \quad \ldots (6)$$

3.3 Arrival/Departure capacity C (DA)

$$C(DA) = C_A(DA) + C_D(DA) = C_A(DA)\cdot\left[1+\sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij}n_{ij\max}\right] \quad \ldots (7)$$

$C_A(DA)$ is the arrival capacity of the runway employing Mixed Mode Operations; $C_D(DA)$ is the correspondent departure capacity; $n_{ij\max}$ is the maximum number of departure aircraft inserted between two consecutive landing aircraft.

4.0 RUNWAY CAPACITY SUBJECT TO ARRIVAL/DEPARTURE PRIORITIES

When the absolute arrival priority is observed, it might be possible to insert a certain number of departure aircraft into the saturated landing traffic flow. In this case, the arrival capacity is at its peak level. To insert more departure aircraft, the separation between landing aircraft pairs have to be extended, which in turn changes arrival/departure priorities and arrival capacity.

Define positive integer *PRI* as the departure/arrival priority index of the runway, *PRI* = 1,2,3,4··· [9]. As a part of the definition, it is prescribed that index *PRI* corresponds to the departure/arrival ratio with the value of *PRI*–1 . It is easy to note that any change of airport fleet mix p_i = (i = 1,2,···n or the priority index *PRI* will cause a change of runway capacity. Several important aspects about index are clarified as follows [9]:

1. When *PRI* = 1 , the service request of arrival aircraft will be first processed by air traffic controller, and the arrival traffic flow reaches its highest density without violating the separation minimum. Only if there is enough space and time separations in

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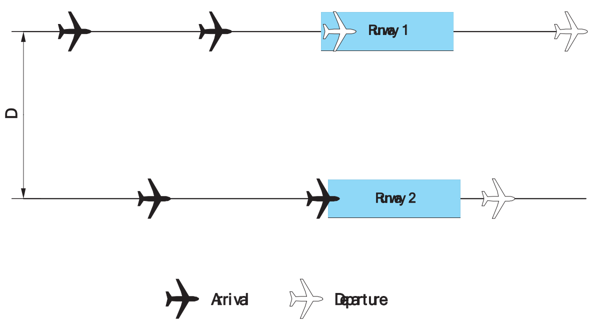

Figure 1. Layout of two parallel runways system.

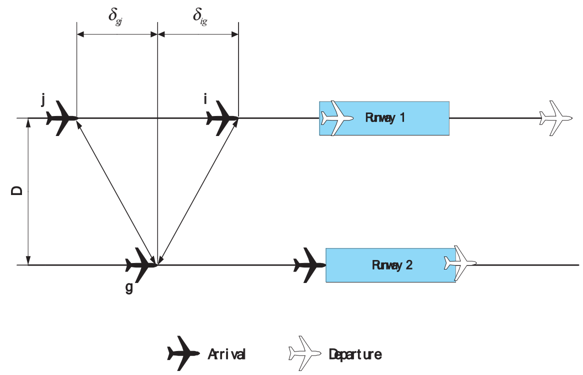

Figure 2. Parallel runways in operation mode two.

the landing traffic flow for insertions of departing aircraft, will the take-off clearance be granted. Arrival capacity in this case is expressed in Equations (1-3).

2. In other priority cases ($PRI \geq 2$), air traffic controllers deliberately delay the response to the service request from arrival aircraft. So adequate time and distance separation will be available for insertion of departure flights. The larger the value of *PRI* is, the longer the arrival service will be held or delayed. It's prescribed that when priority index is *PRI*, the departure traffic amount is approximately arrival traffic amount times ($PRI–1$).
3. When $PRI \geq 2$, the time by which air traffic controller delay arrival service is: $E(DDSR) \times (PRI–1) – [A_{ij}^{k_{ij}}]_{n\times n}$, while the matrix $[A_{ij}^{k_{ij}}]_{n\times n}$ is defined as Runway Idle Time Matrix with its expression shown in Equation (9), and $E(DDSR)$ is the expected value of *DDSR(ij)*.

The delay time of arrival service for $PRI \geq 2$ is expressed as runway delay time matrix $[Delay]_{n\times n}$[9]. The procedure to calculate $[Delay]_{n\times n}$ is introduced as below.

Firstly, for the case of $PRI = 1$, the maximum number of inserted departure aircraft between a consecutive landing aircraft pair of *i* and *j* can be obtained with the methodology introduced in Refs 4 and 9, and this number is expressed as $k_{ij} = n_{ij\max}$ ($i = 1,2,\ldots n$; $j = 1,2,\ldots n$). Since the runway is operating with absolute arrival priority, no delay will be applied to the arrival flight, accordingly, the runway delay time matrix is;

$$Delay = [0]_{n\times n}, \quad PRI = 1 \qquad \ldots (8)$$

Define runway idle time matrix $[A_{ij}^{k_{ij}}]_{n\times n}$ as below;

$$[A_{ij}^{k_{ij}}]_{n\times n} = [T_{ij}]_{n\times n} - [AROR(i)]_{n\times 1}\cdot[1\ldots1]_{1\times n} - [1\ldots1]_{1\times n}^{T}\cdot[DASR(j)]_{n\times 1}^{T} - E[DDSR]\cdot[k_{ij}-1]_{n\times n} \qquad \ldots (9)$$

where $A_{ij}^{k_{ij}}$ indicates the idle time on the runway when the number of inserted departing aircraft between the consecutive landing aircraft *i* and *j* is k_{ij}.

When $PRI \geq 2$, based on the definition of runway delay time matrix, the relationship between $[Delay]_{n\times n}$ and $[A_{ij}^{k_{ij}}]_{n\times n}$ can be described by the following equation;

$$[Delay]_{n\times n} = (PRI-1)\cdot[1\ldots1]_{1\times n}^{T}\, E[DDSR]\cdot[1\ldots1]_{1\times n} - [A_{ij}^{k_{ij}}], \quad PRI \geq 2 \qquad \ldots (10)$$

Thus, after postponing the arrival service when departure/arrival priority index is *PRI*, the time separation between two consecutive arrival aircraft *i* and *j* becomes:

$$T(AA) + [Delay]_{n\times n} = \left[T_{ij}(AA)\right]_{n\times n} + (PRI-1)\cdot[1\ldots1]_{1\times n}^{T}\, E[DDSR][1\ldots1]_{1\times n} - [A_{ij}^{k_{ij}}]_{n\times n}$$

Apparently, the arrival capacity of runway employing mixed mode operations will have various values correspondent to different values of *PRI* as shown in the Equations (11) and (12).

$$C_A(DA) = \frac{1}{E\left[T_{ij}(AA)\right]} = \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij}\cdot T_{ij}(AA)}, \quad PRI = 1 \qquad \ldots (11)$$

$$C_A(DA) = \frac{1}{E\left[T_{ij}(AA) + (PRI-1)\cdot E[DDSR] - A_{ij}^{k_{ij}}\right]} = \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij}\left[T_{ij}(AA) + (PRI-1)\cdot E[DDSR] - A_{ij}^{k_{ij}}\right]} \qquad \ldots (12)$$

$PRI \geq 2$

The departure capacity of the runway employing mixed mode operations $C_D(DA)$ is:

$$C_D(DA) = C_A(DA)\cdot\sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij}\left[n_{ij\,\max} + (PRI-1)\right], \quad PRI \geq 1 \qquad \ldots (13)$$

5.0 CAPACITY MODEL OF TWO PARALLEL RUNWAYS SYSTEM

5.1 Classification of two parallel runways system

According to the distance between the centerlines of two runways (Fig. 1), the two parallel runways systems can be classified into three categories [9]: closely spaced parallel runways ($D < 760$m), intermediately spaced parallel runways ($760\text{m} < D < 1310$m), widely spaced parallel runways ($1310\text{m} < D$).

5.2 Operation strategies

The operation scenarios of the two parallel runways systems can be classified into the following six categories[6,9]:

1. TA: (Two Arrival, which means Both of the two runways are devoted for arrival operation)
2. OAOD: One Arrival One Departure
3. TD: Two Departure
4. OMOA: One Mixed Mode Operations One Arrival, which means one runway accommodates both arrival and departure aircraft, while the other is only for arrival
5. OMOD: One Mixed Mode Operations One Departure
6. TM: Two Mixed Mode Operations.

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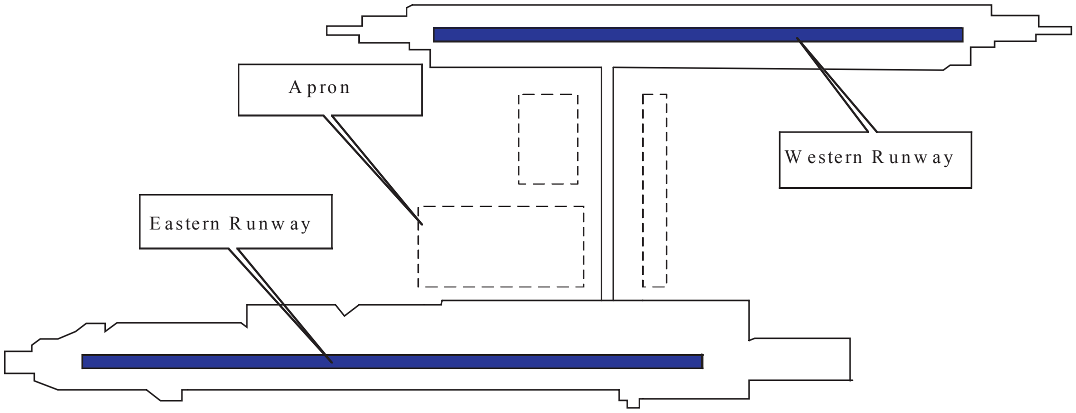

Figure 3. Basic layout of the runways system of an airport.

5.3 Capacity model

The capacity model of two runways system takes various forms, determined mainly by some factors like runways physical layout, relationship between traffic flows of two runways, accuracy of radar surveillance and so on. Full and detailed introduction about this aspect can be found in Ref. 9. In this paper, discussions are focused on the capacity models in two typical operation modes in an airport[6].

5.3.1 Capacity model in Operation Mode One

Operation Mode One features independent approaches plus independent departures, which implicates the arrival and departure traffic flows of one runway are independent of either arrival or departure flow of the other runway[9]. Therefore, while developing the capacity model, the two parallel runways systems can be seen as a pair of segregated parallel runways (see Fig. 1). Considering the situation when both runways implement mixed mode operations (i.e. TM operation scenario), the capacity of the two runways system in this case can be expressed as:

$$C(TM) = 2[C_A(DA) + C_D(DA)] \qquad \text{. . . (14)}$$

where $C_A(DA)$ is the arrival capacity of one runway with mixed mode operations, and $C_D(DA)$ is the departure capacity of one runway with mixed mode operations. The expressions of $C_A(DA)$ is shown in Equations (11) and (12), while $C_D(DA)$ is expressed in Equation (13).

5.3.2 Capacity model of Operation Mode Two

Operation Mode Two features dependent approaches plus independent departures[9]. In this mode, the arrival flow of one runway is dependent on the arrival flow of the other runway, but is independent of the departure flow of the other runway; the departure flow of one runway is independent of the departure flow of the other runway (Fig. 2).

Consider the situation when both runways have mixed mode operations (i.e. TM operation scenario), which is a very typical situation in an airport[6,9]. Among the arrival flow of both runways, departure aircraft will be interspersed when it is required and there is enough time and distance separation between two consecutive landing flights heading to the same runway. And the process of insertion is simplified considerably, because the inserted departing flow will not affect the arrival or departure flow of the other runway.

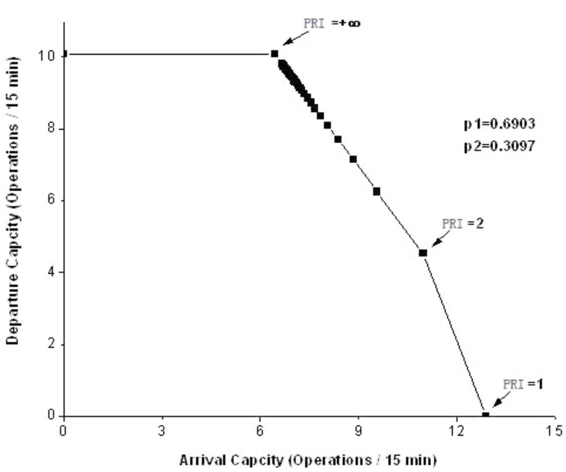

Figure 4. Theoretical capacity curve of an airport in Operation Mode One.

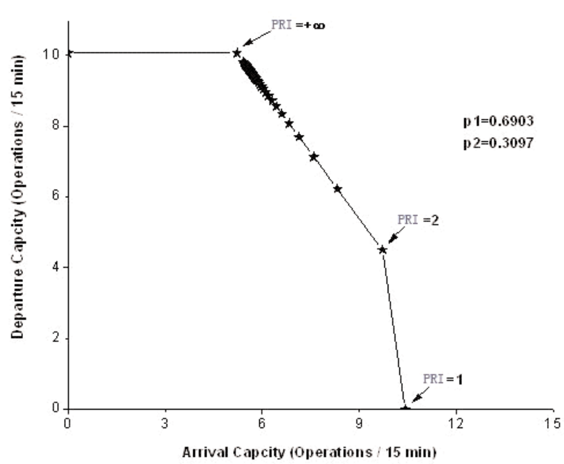

Figure 5. Theoretical capacity curve of BCIA in Operation Mode Two.

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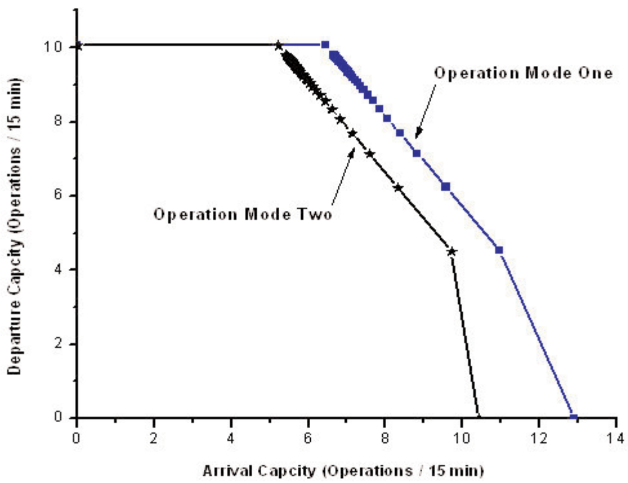

Figure 6. Comparison of theoretical capacity curve in two operation modes.

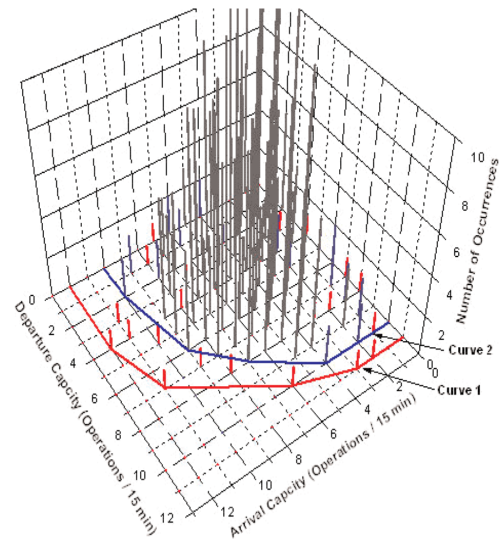

Figure 7. Histogram of airport arrival/departure operations.

Considering the aircraft *i, j* and *g* in Fig. 2, proper distances have to be maintained among them, and the time separation between aircraft *i* and *j* is:

$$T_{ij}(AA) = \sum_{g=1}^{n} p_g \cdot T_{ij}^{g}(AA) \quad \ldots (15)$$

$$T(AA) = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{g=1}^{n} p_i \cdot p_j \cdot p_g \cdot T_{ij}^{g}(AA) \quad \ldots (16)$$

where p_i, p_j, p_g are respectively the proportions of aircraft of type *i*, *j* and *g* in traffic mix. Detailed information of calculation method of $T_{ij}^{g}(AA)$ can be found in Ref. 9.

After obtaining *T*(*AA*), for either one of the two runways with adjustable priority index *PRI*, the arrival capacity $C_A(DA)$ and departure capacity $C_D(DA)$ can be expressed exactly by Equations (11)-(13). And the capacity of the two runways system takes a form exactly as shown in Equation (14).

$$C(TM) = 2[C_A(DA) + C_D(DA)]$$

6.0 INTRODUCTION OF AN AIRPORT

6.1 Runways system

Two parallel runways system of an airport consists of eastern runway and western runway, with a distance of 1960 meters between the runway central lines. According to the relevant ICAO regulations, the runways system can be operated in the mode of independent approaches plus independent departures (i.e. Operation Mode One). However, due to the lack of high-accuracy radar monitoring facilities and qualified air traffic control personnel, the current operation mode of an airport is still dependent approaches plus independent departures (i.e. Operation Mode Two)[6,9].

Mixed mode operations scenario is applied to both eastern and western runways (i.e. TM operation scenario for the two-runways system). One runway is exclusively for landing (designated as major arrival runway), accommodating departing flights only at peak hours when required; and the other runway is mainly for departure (designated as major departure runway), while accommodating landing flights at the same time. Specifically which runway is major arrival Runway or major departure runway varies from time to time, depending on the distribution of the traffic flow and the weather conditions. According to the operational regulations of the local air traffic authority[6,9], on the major arrival runway, the absolute arrival priority is observed, which means *PRI* = 1; while on the major departure runway, the index PRI varies in a way like *PRI* = 1,2,3,4,··· . The physical layout of the two runways of an airport is shown in Fig 3.

6.2 Aircraft fleet

The majority of the fleet operating in an airport comprises heavy aircraft and medium aircraft, while the light aircraft are so few as to be negligible. During the capacity estimation of an airport in this paper, the following wake vortex separation standard is applied[6,9].

Table 1
Separation standard for landing

Trailing aircraft/ Leading aircraft	Medium	Heavy
Medium	6km	10km
Heavy	6km	8km

The number of aircraft types *n* is set to 2, while *i* = 1 represents medium aircraft, and *i* = 2 represents heavy aircraft. Based on an operational record of the week right before Chinese Spring Festival of 2003, the proportions of medium aircraft and heavy aircraft in traffic mix are respectively: $p_1 = 0{\cdot}6903$, $p_2 = 0{\cdot}3097$. More details about other variables used in the capacity evaluation can be found in Ref. 9.

7.0 CAPACITY MODEL OF AN AIRPORT

7.1 Operation Mode One

The capacity model in Operation Mode One has been developed in 5.3.1 of this article. Applying values of relevant variables of the airport and its fleet[6,9] in Operation Mode One to Equations (11)-(13), it is obtained that the capacity of either one of the runways changes in a pattern as below as index *PRI* varies.

While *PRI* = 1

$$C_A^{PRI=1}(DA) = \frac{1}{139{\cdot}4}(oper/s) \quad PRI = 1 \quad \ldots (17)$$

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$$C_D^{PRI=1}(DA) = 0, \quad PRI = 1 \qquad \ldots (18)$$

While $PRI \geq 2$

$$C_A^{PRI\geq 2}(DA) = \frac{1}{19\cdot 98 + 89\cdot 5\cdot PRI}, \quad PRI = 2,3,4,\cdots \qquad \ldots (19)$$

$$C_D^{PRI\geq 2}(DA) = \frac{PRI-1}{19\cdot 98 + 89\cdot 5\cdot PRI}, \quad PRI = 2,3,4,\cdots \qquad \ldots (20)$$

As for major arrival runway, index *PRI* is set to 1 under all circumstances, i.e. *PRI* = 1 ; while for major departure runway, index *PRI* might be different positive integers, i.e. *PRI* = 1,2,3,4···. The two runways system's arrival capacity and departure capacity correspondent to different index *PRI* are shown as follows:
When *PRI* = 1
Arrival Capacity of the two runways system:

$$C_A(TM) = C_A^{PRI=1}(DA) + C_A^{PRI=1}(DA) = \frac{1}{139\cdot 4} + \frac{1}{139\cdot 4} = \frac{1}{69\cdot 7}(oper/s) \qquad \ldots (21)$$

Departure Capacity of the two runways system:

$$C_D(TM) = C_D^{PRI=1}(DA) + C_D^{PRI=1}(DA) = 0 \qquad \ldots (22)$$

When *PRI* = 2,3,4···
Arrival Capacity of the two runways system:

$$C_A(TM) = C_A^{PRI=1}(DA) + \left[C_A^{PRI\geq 2}(DA)\right]_{PRI} = \frac{1}{139\cdot 4} + \frac{1}{19\cdot 98 + 89\cdot 5\cdot PRI}(oper/s), \quad PRI = 2,3,4,\cdots \qquad \ldots (23)$$

where $C_A^{PRI=1}(DA)$ is the arrival capacity of the major arrival runway, and $[C_A^{PRI\geq 2}(DA)]_{PRI}$ is the arrival capacity of major departure runway.
Departure capacity of the two runways system is

$$C_D(TM) = C_D^{PRI=1}(DA) + \left[C_D^{PRI\geq 2}(DA)\right]_{PRI} = 0 + \frac{PRI-1}{19\cdot 98 + 89\cdot 5\cdot PRI} = \frac{PRI-1}{19\cdot 98 + 89\cdot 5\cdot PRI}, \quad PRI = 2,3,4,\cdots \qquad \ldots (24)$$

where $C_D^{PRI=1}(DA)$ is the departure capacity of the major arrival runway, and $[C_D^{PRI\geq 2}(DA)]_{PRI}$ is the departure capacity of major departure runway.

Combining Equations (21) through (24) yields the arrival/departure capacity (operations/second) correspondent to different index *RPI*. By transforming the results into 15-minute capacities (i.e. operations/15 minutes), the capacity of the two runways system in Operation Mode One is shown in Fig. 4.

7.2 Operation Mode Two

The capacity model of Operation Mode Two has been developed in 5.3.2 of this work. Applying values of relevant variables of the airport and its fleet[6,9] in Operation Mode Two to Equations (11)-(13) and (15)-(16), it is obtained that the capacity of either one of the runways changes in a pattern as below as index *PRI* in varies.
While *PRI* = 1.

$$C_A^{PRI=1}(DA) = \frac{1}{172\cdot 5}(oper/s), \; PRI = 1 \qquad \ldots (25)$$

$$C_D^{PRI=1}(DA) = 0, \quad PRI = 1 \qquad \ldots (26)$$

While PRI ≥ 2.

$$C_A^{PRI\geq 2}(DA) = \frac{1}{20\cdot 94 + 89\cdot 5\cdot PRI}, \quad PRI = 2,3,4,\cdots \qquad \ldots (27)$$

$$C_D^{PRI\geq 2}(DA) = \frac{PRI-1}{20\cdot 94 + 89\cdot 5\cdot PRI}, \quad PRI = 2,3,4,\cdots \qquad \ldots (28)$$

It is similar to Operation Mode One for major arrival runway, *PRI* = 1; while for Major Departure Runway, *PRI* = 1,2,3,4···. The two runways system's arrival capacity and departure capacity correspondent to different index *PRI* are shown as follows:
While *PRI* = 1.
Arrival capacity of the two runways system is:

$$C_A(TM) = C_A^{PRI=1}(DA) + C_A^{PRI=1}(DA) = \frac{1}{172\cdot 5} + \frac{1}{172\cdot 5} = \frac{1}{86\cdot 25}(oper/s) \qquad \ldots (29)$$

Departure capacity of the two runways system is:

$$C_D(TM) = C_D^{PRI=1}(DA) + C_D^{PRI=1}(DA) = 0 \qquad \ldots (30)$$

While PRI = 1,2,3,4···
Arrival capacity of the two runways system is:

$$C_A(TM) = C_A^{PRI=1}(DA) + \left[C_A^{PRI\geq 2}(DA)\right]_{PRI} = \frac{1}{172\cdot 5} + \frac{1}{20\cdot 94 + 89\cdot 5\cdot PRI}(oper/s), \quad PRI = 2,3,4,\cdots \qquad \ldots (31)$$

where $C_A^{PRI=1}(DA)$ is the arrival capacity of the major arrival runway, and $[C_A^{PRI\geq 2}(DA)]_{PRI}$ is the arrival capacity of major departure runway.
Departure capacity of the two runways system is:

$$C_D(TM) = C_D^{PRI=1}(DA) + \left[C_D^{PRI\geq 2}(DA)\right]_{PRI} = 0 + \frac{PRI-1}{20\cdot 94 + 89\cdot 5\cdot PRI} = \frac{PRI-1}{20\cdot 94 + 89\cdot 5\cdot PRI}, \quad PRI = 2,3,4,\cdots \qquad \ldots (32)$$

where $C_D^{PRI=1}(DA)$ is the departure capacity of the major arrival runway, and $[C_D^{PRI\geq 2}(DA)]_{PRI}$ is the departure capacity of major departure runway.

Combining Equations (29-32) yields the arrival/departure capacity (operations/second) correspondent to different index *PRI*. Through transforming the results into 15-minute capacities (i.e. operations/15 minutes), the capacity of the two runways system in Operation Mode Two is shown in Fig. 5.

7.3 Comparison of theoretical capacities curves

The theoretical capacity curves of an airport in two different operation modes are both shown in Fig. 6. It's easy to note that both arrival and departure capacities are smaller in Operation Mode Two. The difference between two departure capacities is less than the difference between two arrival capacities, and the maximum of departure capacities of two operation modes remain the same. The reason for such differences is that in both operation modes independent departures is applied, but the strategy of approach varies drastically.

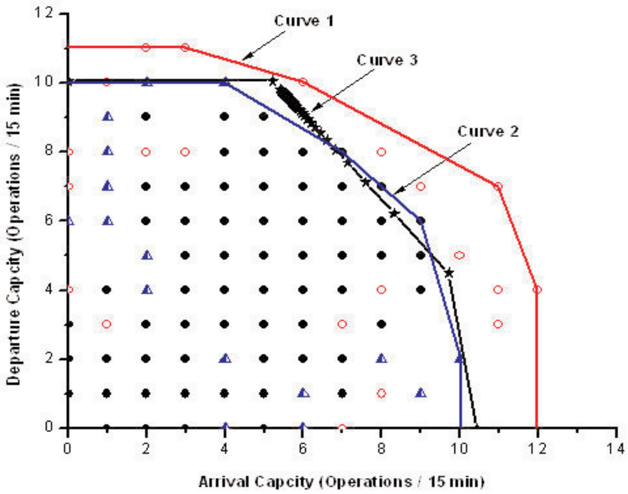

Figure 8. Comparison of capacity curves.

8.0 EMPIRICAL CAPACITY CURVES OF AN AIRPORT

8.1 Empirical estimation of the two runways system's capacity

To obtain the empirical capacity estimation, historical performance data of an airport covering one week right before Chinese Spring Festival of 2003 is used in this paper[9]. Spring festival is observed as the most important traditional holiday in China, and during this period, the airport experiences severe congestions and substantial delays during peak hours. The existence of significant delays can be considered as an indication that the airport operates close to or at its operational limits. In this case, it is reasonable to assume that the historical peak data reflects the maximum operational capabilities, hence be useful to for capacity estimation [7].

Figure 7 illustrates the statistical image of the capacity curves estimates. The bars in Fig. 7 show the number of occurrences of observed pairs of values (arrivals and departures during 15-minute intervals) throughout the period of time considered. The capacity curves are shown as sample two-dimensional percentiles that course through the extreme observations that occur no less than an assigned number. This number reflects the amount of confidence in the capacity estimates and can be heuristically determined. The Percentage of total observations enveloped by a curve determines the corresponding percentile represented by the capacity curve[7]. Curve 1 in Fig. 7 courses through the extreme points that occur at least one time. The capacity curve represents the 100th percentile and is hence not robust. Curve 2 courses through the extreme points that occur no less than two times. The extreme points, which occur only once, have been rejected so as to make the curve robust.

8.2 Comparison of capacity curves

During the period when all the airport performance data was gathered, the two runways system was operating in Operation Mode Two (9). Accordingly, to verify the effectiveness of the analytical capacity model developed in 7.2, the capacity curve obtained through this model is compared with two empirical capacity curves obtained in 8.1.

In Fig. 8, Curve 1 is the non-robust empirical capacity curve, while Curve 2 is the robust empirical capacity curve (the same as in Fig. 7). Curve 3 is the theoretical capacity curve obtained through analytical model in Operation Mode Two.

As shown in Fig. 8, the capacity curve yielded by analytical model is generally located in the area between two empirical capacity curves, and obviously much closer to the robust empirical curve. This result demonstrates that during the determination of the operational limits of airports, the theoretical capacity estimation yielded by analytical model maintains adequate degree of accuracy and satisfactory stability. Distinguished with the convenience of parameters adjustment and engineering application[6], analytical models for airport capacity estimation should have a great potential in air traffic management technology.

9.0 CONCLUSIONS

In this article, the theoretical capacity estimation models (especially analytical models) of two parallel runways system are developed, and the empirically statistic methodology based on historical performance data is discussed as well. Both analytical mathematical models and statistic method are applied to obtain the capacity curves of the two parallel runways system of Beijing Capital International Airport. The demonstration and comparison of the two sets of capacity curves indicates that with a satisfactory degree of accuracy and stability, the analytical mathematical models work effectively in the capacity estimation of the airport with two parallel runways.

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