ENHANCED MODEL FOR TERMINAL AIRSPACE CAPACITY ESTIMATION

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Abstract

Terminal Airspace comprises the area around an airport in which various aircraft in its vicinity are in ascending or descending phases. This paper describes an enhanced model for estimation of Ultimate Capacity of Terminal Airspace, given its geometric layout, traffic data, and the separation minima maintained. This model can be used to determine the number of aircraft in the Terminal airspace of an airport that can be safely handled by the Air Traffic Controllers. An existing probabilistic model for Terminal Capacity assessment was enhanced to include operations on intersecting and parallel runways. An important outcome of this methodology is the minimum time gap between successive operation at the runway, which is utilized to draw a time space diagram of runway operation, and thus obtain an estimate of Delay under various operational scenarios. The model was first utilized to estimate the Terminal airspace capacity of the two most busy airports in India, viz., Mumbai and Delhi, and later for other main Airports viz., Kolkata, Chennai, Ahmadabad, Guwahati, Hyderabad, Kochi and Thiruvananthapuram. A critical analysis of the results lead to suggestions like slot distribution, rescheduling of aircraft, restructuring of spatio-geometrical conditions of airspace and airfield etc. that may be considered to increase capacity and reduce delays at Indian Airports.

Index Terms: Terminal Airspace, Capacity Modeling, Arrival and Departure modeling, Delay and Rescheduling at Airports, Air Transportation Systems

Nomenclature

d = Distance between two parallel runways

\( P_a \cdot P_d \) = Proportion of arriving and departing traffic

\( P_x \) = Proportion of traffic belonging to category ‘x’

\( P_{x/y} \) = Probability of event ‘x’ to happen, given that event ‘y’ has happened

\( P_{ij} \) = Probability that the aircraft ‘i’ is followed by aircraft ‘j’

\( k_l P_{ij} \) = Probability of having a sequence where the leading aircraft ‘i’ coming from/departing to the terminal gate ‘k’ and the trailing aircraft ‘j’ coming from/departing to the terminal gate ‘l’

\( R_1, R_2 \) = Runway 1, 2

\( s_o \) = Initial separation to be ensured

\( s(t) \) = Separation at the time instance ‘t’

\( k_l S_{ija} \) = Distance between terminal entry gate ‘i’ and trailing aircraft ‘j’ measured along the trajectory ‘ija’ to be followed by it at time t=0, which is the moment when the leading aircraft has just entered the its terminal entry gate

\( k_l S_{ij}(t) \) = Horizontal separation between leading and trailing aircrafts ‘i’ and ‘j’, entering terminal entry gates ‘k’ and ‘l’ respectively

\( k_l S_{ijd} \) = Distance between runway threshold and leading aircraft ‘i’ measured along the trajectory ‘ijd’ at time t = 0, which is the moment when the trailing aircraft has just started to roll-off

\( k_l S_{ijd}(t) \) = Horizontal separation between leading and trailing aircrafts ‘i’ and ‘j’, departing to terminal gates ‘k’ and ‘l’ respectively

\( t \) = Mean inter arrival / departing time at the runway threshold

\( t_1, t_2 \) = Time of utilization of each of intersecting runway

\( t_{chover} \) = Time required for a controller to change from one runway to other

\( k_l t_{ij} \) = Inter arrival/departure time measured at runway threshold between two aircraft ‘i’ and ‘j’ traveling on trajectories from runway threshold to terminal gate ‘k’ and ‘l’

\( t_{ROT} \) = Runway occupancy time of initial aircraft

\( t_{xy} \) = Time difference between the operations ‘x’ and ‘y’

\( v_j, u_j \) = Velocities of trailing aircraft ‘j’ along its trajectory

\( v_i, u_i \) = Velocities of leading aircraft ‘i’ along its trajectory

\( w_i \) = Velocity of leading aircraft along the final approach path

\( x_p, y_j \) = Coordinates of position vector of ‘p’th aircraft

\( x_i, y_i, z_i \) = Coordinates of position vector of ‘i’th aircraft

\( x_k, y_k, z_k \) = Lengths of segments along trajectory connecting terminal gate ‘k’ to the runway threshold traveled by the first aircraft in the departing phase such that it maintains a minimum separation from next aircraft

\( x_{ko}, y_{ko} \) = Lengths of segments along trajectory connecting terminal gate ‘ko’ to the runway threshold

\( x_{k'}, y_{k'}, z_{k'} \) = Lengths of segments along trajectory connecting terminal gate ‘kk’ to the runway threshold

\( x_f, y_f, z_f \) = Lengths of segments along trajectory connecting terminal gate ‘f’ to the runway threshold

\( \alpha, \beta \) = Angles between different segments of the trajectory joining terminal gate and runway threshold

\( \alpha_k, \beta_k \) = Angles between different segments of the trajectory, joining terminal gate k and runway threshold

\( \alpha_f, \beta_f \) = Angles between different segments of the trajectory, joining terminal gate ‘f’ and runway threshold

\( \delta_j \) = Minimum horizontal separation to be maintained

\( \delta^*_{ij} \) = Minimum horizontal separation to be maintained for parallel runway operation

\( \gamma_{ij} \) = Length of the common final approach path
\( \lambda_{R1} \), = Runway Capacity
\( \lambda_{R2} \)
\( \lambda_a \), = Ultimate arrival Capacity
\( \lambda_d \), = Ultimate departure Capacity

**Introduction**

Globalization of air transportation industry and the fast pace of technology development has initiated a paradigm change in air transportation industry. According to the International Civil Aviation Organization (ICAO), the largest growth in air traffic during the last decade has been in the Asia and Pacific region. ICAO forecasts the traffic to grow by 4.1% in this region while the global traffic will grow up only by 2.5%. Airbus industry forecasts that by 2015, the annual growth in this region is likely to be around 12.7%. As per the prediction made by Government of India, the Civil Aviation sector is on a roll, with both state-owned and private carriers adding more capacity and launching more connections globally, as air traffic to and from India continues to grow nearly 20% annually.

Domestic air traffic grew at an impressive 46% in 2006. While passenger traffic in metros grew by an average of 31%, smaller stations like Port Blair, Nagpur and Raipur registered traffic growth of 141.8%, 94.8% and 70.3%, respectively. According to Airports Authority of India data, of the top 45 airports, nine airports registered 50% growth in passenger traffic. These include Hyderabad, Pune, Coimbatore, Mangalore, Nagpur, Port Blair, Raipur, Ranchi and Jaipur. Surprisingly, two of the most popular tourism destinations- Udaipur and Jodhpur- recorded only 9.6% and 2.9% growth, respectively.

The total aircraft movements in the country increased to 779 from 620 in April to December 2006 over the corresponding period of 2005, a growth of almost 30%. Total passenger movement in the country increased 33%, with domestic traffic accounting for 41% of the growth and international traffic contributing only 15%.

The main drivers of traffic growth are economic upswing, concentration of population, wealth generation, industry modernization and increasing liberalization, leading to a higher propensity to travel. To add to this, there are penetrations of low-cost air carriers, which are offering exceptionally low airfare that can be compared with railway fares in air conditioned class. The growth in commercial air services continues to outstrip the available capacity at more and more airports. Because of the interconnected operation of the national air transport system, capacity constraints at some airports impact on other airports. Environmental, economic, political and physical constraints on airport capacity have, in some instances, exacerbated this problem. Governments, airlines and airports have each developed measures to overcome situations of insufficient airport capacity. However the increase in commercial operations has lead to the need for increase in the overall capacity of Indian airspace, and not just the airport.

An urgent need is being felt for a critical review of the airspace and air-routes around busy airports, such as Mumbai, so that larger number of aircraft can be handled, without compromising on the safety. This paper describes a methodology to estimate the current capacity of a given airspace, given its geometric layout, traffic data and the separation minima to be maintained. The sections that follow provide a brief description of the ATM system, and explain the basic concepts related to estimation of capacity of the terminal airspace. Details of a methodology for estimation of terminal airspace capacity an airport based on two existing runway and terminal capacity models are then provided, along with the results of its validation with a past study for Belgrade airport. Details of an exploratory study that was carried out to estimate the ultimate capacity of terminal airspace at Mumbai airport are presented. Results for terminal airspace capacity of some major airports in India are also presented.

**Brief Description of an Air Traffic Management System**

Air Traffic Management (ATM) system is established over the airspace to provide safe, efficient and regular air traffic. The system should be able to detect and resolve conflicts between aircraft and guarantee separations without any significant delays. To fulfill the above conditions, the ATM system divides the large airspace into smaller sections; such divisions occur at two levels. On the first level, the En-route Airspace, Terminal Airspace and the final approach or Airport Zones are demarcated. In the second level, these areas are sub-divided into ‘ATC sectors’, which are assigned to one or more air traffic controllers who are responsible for monitoring and controlling the air traffic in them. The ascending traffic in departure phase and the descending traffic in arrival stage come under the Terminal Airspace and controlled by Terminal Airspace Controller. For further details of the ATM system, one can refer to official documentation issued by regulatory bodies such as FAA [2002, 2004, 2005], or...
specialized literature, such as Tosic and Horonjeff [1976], Janic and Tosic [1982] and Nolan [2004].

Terminal Airspace

Terminal Airspace is usually represented in the form of a prism with polygonal shaped base, whose corners are the entry gate to this airspace, as shown in Fig.1. Gates are common points between the Terminal Airspace and the En-route Airspace. These gates are usually defined by the presence of navigational aids on the ground, and in most cases, the trajectory to be followed from the Terminal Gate to the Runway Entry Gate by an arriving aircraft is pre-decided, based on the location of these navigational aids. Each of these are otherwise specified as points in the three dimensional airspace. For ease in controlling the air traffic, all aircraft must follow these trajectories to land, and hence they are called as the 'Standard Approach Routes' (STARS). These trajectories can be generated by mission computers onboard the aircraft, or the aircraft can be directly routed along them by the ground based Air Traffic Controllers.

Trajectories of all the arriving aircraft which land on a specific runway converge through the airspace to a point, which is located vertically above the extended Runway centerline. This point, called the Runway Entry Gate, is normally near the outer runway marker of the Instrument Landing System (ILS). The starting point on the runway where the pilot is expected to commence the landing procedure is called the Runway Threshold. The trajectory followed by all arriving aircraft from the Runway Entry Gate to the Runway Threshold is called the Final Approach Path, which is the last segment of flight, common and equal in length to all aircraft that land under ILS procedure. On the same lines, there exists a Runway Departure Gate for all departing aircraft. These Entry and Departure Gates are the points of interaction between the Terminal Airspace and the Runway subsystem. An increase in the number of runways will allow simultaneous approach and landings, and thus increase the capacity of the airspace. Hence the Terminal Airspace is a subsystem that is in continuous interaction with both the En route Airspace and the Runway subsystems.

Survey of Literature

To estimate the capacity of a Terminal Airspace, one needs to know its geometrical layout, and the factors that influence its capacity. Blumstein [1960] has put forward the basic model for estimation of the capacity of an airspace and airport forward. He defined two types of capacities, viz., Ultimate and Practical. Ultimate capacity was defined as the maximum number of aircraft that can be handled by a facility during a specified time period, under condition of continuous demand. Theoretical approaches can only model the Ultimate capacity, since it cannot cater to any delay that may exist in processing the aircraft. Practical Capacity, on the other hand, was defined as the number of aircraft operation that can be handled by a facility during a specific period of time, such that average delay to all processed aircrafts equals to a certain specified amount. The Practical Capacity can be estimated by constraining Ultimate Capacity with Air Traffic Controller workload.

Estimation of the airspace capacity involves the following three consecutive steps suggested by Hockaday and Kanafani [1974]:

- **Aircraft Separation Estimation**: Calculating the time interval between and two operations such that the minimal separation as required is maintained.
- **Capacity Computation**: Manipulation of these intervals of time so as to estimate the capacity of the airspace.
- **Operational Strategy Selection**: Selection of operational strategy so as to produce the highest capacity.

Ultimate capacity of the runway depends on several factors like the separation minima to be maintained, proportion of aircraft mix, location of exit taxiways, the geometry of the approach paths associated with the runways and the speed of the approaching aircraft. Horonjeff and McKelvey [1983] started initial mathematical modeling of capacity estimation. Runway Capacity Model was formulated by Tosic and Horonjeff [1976] to compare Microwave landing system and Instrument Landing System. This Runway Capacity Model was extended by Janic and Tosic [1982] to estimate Arrival capacity of Terminal Airspace.

**Terminal Airspace Arrival Capacity Model**

Figure 2 provides a pictorial representation of the modeling of the Terminal Airspace.

The capacity of the terminal airspace $\lambda$ is estimated as:

$$\lambda = 1/\left( \sum_{ijkl} k_{ij} f_{ij} P_k P_{l/k} P_{j/l} \right)$$

(1)
Where,

\[ k_{ij}^t = p_{kl} P_{i/k} P_{j/l} \text{ or } P_k P_l P_{i/k} P_{j/l} \]  \hspace{1cm} (2)

and \( k_{ij}^t \) is the inter operational time gap between aircraft \( i, j \) operating from terminal entry gate \( k, l \) respectively, is calculated from equation

\[
k_{ij}^t = \left( ( ( x_{i} + x_{j}) / v) + ( ( y_{i} + z_{j}) / u) \right) - \left( ( x_{i} / v) + ( ( y_{i} + z_{j}) / u) \right)
\]  \hspace{1cm} (3)

Inter-arrival time \( k_{ij}^t \) for any given pair of aircraft is an increasing function of initial separation \( k_{ij} S_{ijo} \). The flow through runway entry gates can be maximized by minimizing the inter arrival time \( k_{ij} S_{ijo} \) as follows:

Minimize

\[
k_{ij}^t = \min \{ t \mid k_{ij}^t S_{ijo} > \delta \} \text{ for all } t \leq \left( ( x_{i} / v) + ( ( y_{i} + z_{j}) / u) + (\gamma / w) \right)
\]  \hspace{1cm} (4)

The distance between two aircraft ‘\( i \)’ and ‘\( j \)’ coming from terminal entry gates ‘\( k \)’ and ‘\( l \)’ is even more complex function than \( y_{ij} S(t) \) in the estimation of Runway capacity. This function can be written as:

\[
k_{ij} S(t) = \frac{S(v, u, x, y, z, \alpha, k, \beta, \gamma, \delta)}{x_k(x_k, y_k, z_k)}
\]  \hspace{1cm} (5)

Equation 5 is a complex trigonometric function, which changes as aircraft travels from one segment to other segment, and all its elements are explained in Fig.4. For a given trajectory and aircraft mix all the terms in Eqn.5, except \( k_{ij} S_{ijo} \) and ‘\( t \)’ can be considered as parameters. So, the moment \( t^* \) of the minimum distance between aircraft pair \( k_{ij} S_{ij} \) min = \( k_{ij} S_{ij} (t^*) \) can be found, and for \( k_{ij} S(t^*) = \delta_{ij} \), corresponding \( k_{ij} S_{ijo} \) and \( k_{ij}^t \) can be computed. Hence, \( k_{ij}^t \) and \( p_{kl} P_{i/k} P_{j/l} P_{l/k} P_{j/l} \) can be computed, and thus the Terminal capacity \( \lambda \).

**Terminal Assumptions in the Terminal Airspace Model**

The following assumptions were made by Janic and Tosic [1982] to simplify the modeling task.

- Only arriving aircraft are considered, and that too in a single runway layout.
- The trajectory is modeled as a three segment ‘Dog Leg’ trajectory.
- There is continuous demand for service by arriving aircraft i.e., the system is never waiting for an arriving aircraft.
- Velocity of aircraft remains same throughout in each segment and changes from segment to segment instantaneously with the change in heading.

**Ultimate Capacity Modeling**

**Calculation of Initial Separation for arrival phase**

Equations pertaining to the inter separation distance as given out in Terminal Airspace Model, by Janic and Tosic [1982] could not be modified for extending it to departure phase. So, those equations of inter separation distance were derived a fresh from the geometry of airspace, relative placement of gates and from characteristics of an aircraft.

Let \( x_i(t), y_i(t) \) be the position coordinates of the ground trace of \( i^{th} \) aircraft and \( x_j(t), y_j(t) \) be the coordinates of \( j^{th} \) aircraft on their way from their respective gateways to Runway threshold. These coordinates can be given by set of equations as follows:

\[
x_i(t) = z_i(t) + x_i(t) \cos \beta_i(t) + x_k(t) \cos \alpha_i
\]

\[
y_i(t) = y_i(t) + \sin \beta_i(t) + x_k(t) \sin \alpha_i
\]

\[
x_j(t) = z_j(t) + x_j(t) \cos \beta_j(t) + x_k(t) + kl S_{ijaw}(t) \cos \alpha_i
\]

\[
y_j(t) = y_j(t) + \sin \beta_j(t) + x_k(t) + kl S_{ijaw}(t) \sin \alpha_i
\]  \hspace{1cm} (6)

Then the separation between two aircraft at any instance of time can be given as

\[
kl S_{ijaw}(t) = \sqrt{(x_i(t) - x_j(t))^2 + (y_i(t) - y_j(t))^2}
\]  \hspace{1cm} (7)

This equation is further used to validate the model against results produced by Janic and Tosic [1982].

**Departure Modeling**

Modeling of departure phase of flight is done in parallel lines to that of arrival capacity modeling. Here we introduce a term called ‘Initial Departure separation dis-
Determination of Initial Separation and Inter Departure Time

This section explains the computation of inter departure time at runway exit gates as well as corresponding initial separation. For each pair of departing aircraft $i$, $j$ going to terminal entry gates ‘$k$’ and ‘$l$’ respectively, the inter departure time at runway departure gate can be represented as:

$$ kl\, t_{ij} = \left( \frac{x_{ko} + y_{ko} + z_{ko}}{u_i} \right) $$

(8)

It may be noted that $kl\, t_{ij}$ for any given pair of aircraft is an increasing function of initial separation $kl\, S_{ijdo} = x_{ko} + y_{ko} + z_{ko}$. The flow from runway departure gates can be maximized by minimizing the inter departure time $kl\, S_{ijdo}$ as follows:

Minimize $kl\, S_{ijdo}$ s.t. $kl\, S_{ijd}(t) > \delta_{ij}$,

for all $t \leq \left( \frac{x_{\bar{k}} + y_{\bar{k}} + z_{\bar{k}}}{u_{\bar{k}}} + \frac{y_{\bar{j}}}{w_{\bar{j}}} \right)$

(9)

The distance between two aircraft ‘$i$’ and ‘$j$’ departing to terminal entry gates ‘$k$’ and ‘$l$’ is a complex function of $kl\, S_{ijdo}$. Let $x_j(t), y_j(t)$ be the position coordinates of the ground trace of $i^{th}$ aircraft and $x_j(t), y_j(t)$ be the coordinates of $j^{th}$ aircraft on their way from their respective gateways to Runway threshold. These coordinates can be given by following set of equations.

$$ x_j(t) = z_j(t) + \gamma_j(t) \cos \beta_j + x_j(t) \cos \alpha_j $$
$$ y_j(t) = y_j(t) + \sin \beta_j + x_j(t) \sin \alpha_j $$
$$ x_j(t) = z_j(t) + \gamma_j(t) \cos \beta_j + x_j(t) \cos \alpha_j $$
$$ y_j(t) = y_j(t) + \sin \beta_j + x_j(t) \sin \alpha_j $$

(10)

In the above equations when $x_j(t), y_j(t), z_j(t)$ starts from zero, $x_k(t), y_k(t), z_k(t)$ starts with initial value $x_{ko}, y_{ko}, z_{ko}$ such that $kl\, S_{ijdo} = x_{ko} + y_{ko} + z_{ko}$. Then the separation between two aircraft at any instance of time can be given as

$$ kl\, S_{ijd}(t) = \sqrt{(x_i(t) - x_j(t))^2 + (y_i(t) - y_j(t))^2} $$

(11)

This equations can be used to find the inter departure time between two aircraft.

Inter Operational Time and Runway Occupancies

The above theory discussed is used to find inter operational (arrival / departure) time between any two aircraft in different phases of flight. As a rule no two aircraft is allowed to occupy the same runway at a given instant of time. So these inter-operational times are compared to the Runway occupancy time of former aircraft and are reset if they are not high enough to allow former aircraft to vacate the runway.

Check $t_{ij} \geq t_{ROT}$ else $t_{ij} = t_{ROT}$

(12)

Arrival / Departure Distribution

Arrival and Departure traffic changes from hour to hour through the day. So this distribution was incorporated into the modeling to help the model calculate hourly capacity of the airspace for a given hour. Thus hourly capacity $\lambda$, for an hour when the arrival to departure ratio is $p_a : p_d$ is given by

$$ \lambda = \lambda_a^* \cdot p_a + \lambda_d^* \cdot p_d $$

(13)

Extension of the Model for Special Runway Alignment

The model developed by Janic and Tosic [1982] for a single runway layout described above was implemented as MATLAB code, and further enhanced by Bagg and Punt [2006] to include Intersecting Runways and Parallel Runways. In this section, these enhancements are briefly described, which allow the estimation of the Terminal airspace the capacity, when multiple runways are in operation.

Intersection Runway Operation

Let $R_1, R_2$ be two runways in a specified Airspace. Let the time of utilization of Runway $R_1$ is $t_1$ and that of runway $R_2$ is $t_2$, while the ultimate capacities (of arrival / departure individually) that is handled are $\lambda_1$ and $\lambda_2$. Then Ultimate capacity that the airspace can handle is given by
\[ \lambda = \frac{(\lambda_1 t_1 + \lambda_2 t_2 + t_{\text{chover}})}{(t_1 + t_2 + t_{\text{chover}})} \]  

(14)

Parallel Runway Operation

There are two types of operation when we consider parallel Runway operation, viz. Simultaneous and Parallel Operation. In simultaneous operations i.e., the two parallel runways are used one after the other repeatedly, the distance of separation between given pair of runway \( d \) is less than the separation minima rules followed in the airspace \( \delta_{ij} \). Then actually both the runway can be considered as a single runway operating with a different separation rules as described in Fig.3.

Hence, for \( d < \delta_{ij} \), we need to find
\[ \delta_{ij}^* = \sqrt{\delta_{ij}^2 - d^2} \] which is the modified distance of separation distance then the same code above can be run for arrival, departure or both according to its usage.

The second type of operations is parallel operations, where the capacity of the airspace in just an addition of capacities of individual runway.

\[ \lambda = \lambda_{R_1} + \lambda_{R_2} \]  

(15)

But in both of these cases we need to take care of distribution of traffic as a few runways may only be fit for operation of small and medium sized aircraft.

Validation

The model was validated against the results quoted by Janic and Tosic [1982] for their study on Belgrade Airport, as shown in Fig.4 Points marked with ‘*’ and ‘o’ are actual results presented in by Janic and Tosic [1982] and Janic [2000].

Exploratory Study for Estimation of Capacity of Mumbai Terminal Airspace

Using this methodology, an exploratory study for estimation of Capacity of the Terminal Airspace around Mumbai airport was carried out. Aircrafts were classified as per their wake turbulence category Heavy, Medium and light reported by ICAO [1978]. These results were further cross checked with results generated with the model developed by Odoni 1998 and the results are presented below.

Estimation of Capacity at Mumbai Airport

Traffic data over Mumbai Terminal Maneuver Area (TMA) was obtained from the Airports Authority of India cited in Private Communication [2005]. A study of nearly a thousand aircraft that flew over Mumbai FIR revealed that ~ 530 aircraft (~ 250 departing and ~ 260 arriving) operate from Mumbai airport, which represents an average capacity of around 22 aircraft per hour. Table-1 shows the mix of traffic in terms of type of aircraft i.e., Heavy, Medium and Light; it can be seen that a very large proportion constitute the Medium type.

Separation minima of 8 nm were assumed, in keeping with the current ATC procedure being followed in Mumbai TMA. The model was applied to this data, and for the traffic mix shown in Table-1, the Capacity of Mumbai TMA was estimated to be between 27 to 28 operations per hour.

Sensitivity of Capacity to Separation Minima and Traffic Mix

Figure 5 shows variation of Capacity of Airspace with variation in separation minima between two aircraft. It is clearly evident that as the separation minima increases, the constraints get tighter, and hence the capacity of both arrival and departure, decreases.

In Fig.6, the arrival and departure capacity is plotted against the change in traffic mix. In this case, the proportion of Light Aircraft is ignored. It is assumed that all aircrafts are Medium and Heavy. Hence, the variation in capacity is observed with increase in proportion of Light Aircraft. As summarized in these figures the results generated by Odoni [1998] model and the enhanced capacity model by Bagg and Pant [2006] are comparable.

| Table-1 : Breakup of Heavy, Medium and Light Aircraft |
|---------------------------------|--------------|---------------|
| Light Aircraft (%) | Medium Aircraft (%) | Large Aircraft (%) |
| Arrival | 02 (0.8) | 218 (77.3) | 62 (21.9) |
| Departure | 02 (0.8) | 194 (78.5) | 51 (20.7) |
Sensitivity of Capacity to Traffic Mix and Separation Minima

Figure 7 shows variation of Capacity of Airspace with Separation minima between two aircraft and illustrates the effect of constraints on Runway occupancy time. Flattish part of curve in Fig.7 shows that as the separation minima increases the inter-operational time is nearly equal to Runway occupancy and thus the constraints are less serious, but when separation minima is less constraints are more serious.

Figure 8 shows variation of the airspace capacity with and without constraints of Runway occupancy time. Till proportion of medium aircraft is less than 0.55 the variation of capacity with and without constraints is similar but after then the increase of capacity is constraints by runway occupancy time.

Sensitivity of Capacity to Inter Aircraft Separation Across Airports

A similar study on effect that the separation between the aircrafts has on the capacity on Terminal Airspace of respective airports is summarized in Table-2. The following results show that as the separate on distance between two successive aircrafts reduce overall capacity that can be supported by the airspace increases. This also shows that though there is an additional capacity that can be added on a terminal airspace by reducing the separation distance that is allowed between two aircrafts the amount of additional capacity available depends on the shape of the airspace and relative location of its entry and exit gates.

It also depends on the relative positions and relative alignment of runways and their relative utilization.

Estimation of Delay

Inter-operational time calculated in the above capacity model can be applied to study delay at an Airport. Aircraft are actually scheduled to find delay incurred in the present schedule. Scheduling is carried out in accordance with the following ATC rules suggested by Horonjeff and McKelvey [1983]:

• No two aircraft are allowed to exercise operation on the runway at the same time.
• Arriving aircraft have a priority in the usage of runway over departing aircraft.
• Departures may be released if the runway is clear and the subsequent arrival is at least a certain distance from the runway threshold.
• Some minimum time gap is maintained between two departing aircraft (as a function of former aircraft being arrival or departure)

Time gap between two successive operation is taken from the inter operation time matrix calculated in the above Ultimate Capacity Model. Criteria of Runway usage are discussed in Table-3.

For operations of Arrival-Arrival and Departure-Departure separation criterion is taken from the model, the

| Table-2 : Sensitivity Analysis of Effect of Inter Aircraft Separation on Terminal Airspace Capacity |
|-----------------|---|---|---|---|---|---|---|---|---|---|---|
| Separation      | 8 nm | 7 nm | 6 nm | 5 nm | 4 nm |  |
| Airport         |  |  |  |  |  |  |  |  |  |  |
| Kolkata         | Arv | Dep | Total | Arv | Dep | Total | Arv | Dep | Total | Arv | Dep | Total | Arv | Dep | Total | Arv | Dep | Total |
|  | 15  | 37  | 21  | 16  | 38  | 25  | 18  | 40  | 28  | 20  | 42  | 30  | 24  | 45  | 32  |  |
| Chennai         | 16  | 40  | 28  | 18  | 45  | 32  | 22  | 50  | 35  | 24  | 56  | 40  | 28  | 59  | 44  |  |
| Delhi           | 18  | 33  | 24  | 21  | 35  | 26  | 24  | 38  | 28  | 26  | 42  | 32  | 32  | 48  | 38  |  |
| Ahmedabad       | 15  | 19  | 17  | 17  | 21  | 19  | 23  | 20  | 21  | 26  | 24  | 25  | 31  | 33  | 31  |  |
| Bangalore       | 9   | 25  | 18  | 11  | 27  | 20  | 14  | 29  | 22  | 19  | 33  | 27  | 26  | 38  | 33  |  |
| Guwahati        | 21  | 32  | 27  | 24  | 34  | 29  | 29  | 36  | 33  | 34  | 36  | 36  | 43  | 44  | 43  |  |
| Hyderabad       | 11  | 23  | 18  | 13  | 25  | 20  | 15  | 28  | 22  | 20  | 36  | 26  | 27  | 37  | 32  |  |
| Kochi           | 12  | 21  | 17  | 14  | 22  | 18  | 17  | 24  | 21  | 22  | 26  | 24  | 30  | 30  | 30  |  |
| Thiruvananthapuram | 13  | 25  | 17  | 13  | 29  | 19  | 13  | 33  | 21  | 13  | 40  | 24  | 13  | 51  | 28  |  |
initial separation ($\delta_{ij}$) guaranteed with respect to leading, and trailing aircraft as put forward by [ICAO. 1978].

Figure 9 shows delays that occur while following the present schedules of the aircraft as per the flight plans filed at Mumbai airport. These results indicate that the maximum delay to arriving and departing aircraft is 1 hour 6 minutes and 1 hour 13 minutes, respectively and the average delay to arriving and departing aircraft is around 33 minutes and 59 minutes, respectively.

The delay study was repeated with variation of inter-separation distance $\delta_{ij}$, which shows that the average delay reduces as separation criterion is reduced. The study also showed that introduction of intersecting runway into operation led to reductions in delay in arrival and departure, as shown in Fig.10 and Fig.11.

### Rescheduling

The flight schedules as per the flight plan data obtained from AAI [Private Communication 2005] were rescheduled up to one hour, to see if that results in reduced delays. The results are presented in Table-4, which indicate that such rescheduling was more effective in reducing delays in arrival, rather than departure.

Departure traffic could not be completely rescheduled, since max departure delay occurs at the peak hour, where the delay passes on from one departure aircraft to another. The average delay in both the case reduces showing that there are gaps in the schedule that can be utilized to optimize capacity and delay at an Airport.

Figure 12 is a reproduction of Fig 9 with the rescheduled data. This shows that at peak hour for departure delay i.e. 12:00 to 15:00 hrs the max departure delay shifts in terms of which flight it occur but do not reduce in magnitude. It can be seen that delays for many flight are almost zero as they lie on the X axis itself.

### Sensitivity of Delay to Increase in Demand

The flight plan data was increase in percentage to study sensitivity of Delay to increase in Demand of Travel. Flights were uniformly added up each hour such that the distribution of traffic is maintained as it is today. Statistics regarding the traffic proportions and gate proportion were also maintained, uniform. The delay characteristics were obtained both with and without perpendicular runway simultaneously operating.

Figure 13 and 14 shows peeking of the average arrival and departure delays when arrival is priorities over departure when traffic increases.

### Conclusions and Future Work

Study of runway occupancy time constraints showed that increase in number of rapid exit taxiways, thus reducing Runway occupancy time will increase Capacity of the Airport. Rescheduling of Aircraft will reduce delays at the Airport and thus will aid increasing the daily capacity of the airport. A few aircraft need to be drastically relocated from peak hours to non peak hrs so that airport is made un-congested.

This methodology needs to be extended to interactions between airports. Even the over flying aircrafts needs to be included into the study. Constraints posed by Controller workload needs to be incorporated.


Fig. 2 Terminal Airspace Model as per Janic and Tosic [1982]

Fig. 3 Parallel Operation Case 1

Fig. 4 Validation of Results Against Presented by Janic [1982, 2000]

Fig. 5 Capacity Variation with Increase in Separation Minima - Mumbai

Fig. 6 Variation of Capacity with the Aircraft Mix - Mumbai

Fig. 7 Capacity Variation with Increase in Separation Minima and Constrained by ROT

Fig. 8 Variation of Capacity with the Aircraft Mix
Fig. 9 Piling up of Delays Over a 24 Hour Period

Fig. 10 Arrival Delay with Variation of Separation Minimum

Fig. 11 Departure Delay with Variation of Separation Minimum

Fig. 12 Change in Delay Characteristics with Rescheduled Flight Data

Fig. 13 Variation of Average Delay per Arriving Aircraft as Demand Increase

Fig. 14 Variation of Average Delay per Departing Aircraft as Demand Increase