ANDREJ GREBENŠEK, B. Sc.
Ministarstvo za promet
Uprava Republike Slovenije za civilno letalstvo
Kotnikova 19a, 1000 Ljubljana, Republika Slovenija
e-mail: andrej.grebensek@caa-rs.si
STANISLAV PAVLIN, D. Sc.
Sveučilište u Zagrebu
Fakultet prometnih znanosti
Vukelićeva 4, 10000 Zagreb, Republika Hrvatska

Technology and Management of Traffic
Preliminary Communication
U. D. C.: 625.717.3
Accepted: Feb. 28, 2003
Approved: Dec. 10, 2003

CALCULATION OF THE RUNWAY CAPACITY OF LJUBLJANA – BRNIK AIRPORT

ABSTRACT

Ljubljana Airport is the main and central airport of the Republic of Slovenia that serves the needs of the major part of the country as well as the needs of the eminent regions across the border. Due to its proximity to the capital of Slovenia, it is of special importance for the country. The traffic at Ljubljana Airport consists of IFR and VFR traffic. In calculations, however, only IFR traffic is considered. Although the VFR traffic participates with a significant share in the total amount of traffic, it is so flexible that in the end, it only contributes to the overall capacity of the runway.

Ljubljana Airport is specific because there is no taxiway till the holding position of runway 31. Aircraft generally land on runway 31. This is the only available instrumental runway for landing. Take-offs can be executed in the directions 31 or 13. Both directions are considered in the calculations. The basic calculations are done on the assumption that take-offs and landings are executed in the same direction, that is, on runway 31. This presents a normal procedure at traffic peaks since such a situation is clearer, easier and safer for an Air Traffic Controller to handle. The present traffic load at the airport is not so heavy, therefore in quieter periods of the day aircraft land on runway 31 and take off from runway 13. This procedure reduces the capacity of the runway and the calculations for it have been carried out at the end.

KEY WORDS

air traffic, runway, capacity, take-off, landing

1. INTRODUCTION

Over the past twenty years, air traffic in Europe has reached the highest rate of growth among all types of transport. Since 1980 the traffic, calculated in pkm, has increased by 7.4% per year. The traffic at airports, on the other hand, has increased five times since 1970 [1]. Every year that passes by brings the European airport infrastructure more to its limits. Some airports are already at the point of saturation and therefore have to refuse new carriers, which means less competition and worse service to the customers.

The biggest problem in air traffic are the delays that on the average last about half an hour per flight. In Europe, about 30% of flights are generally delayed. Delays are the longest during the summer season. At the airports, delays occur due to the lack of capacity since the traffic growth is faster than the expansion or the upgrade of the infrastructure.

Primary Delays are usually the most common cause for overall delays (Figure 1). They are the result of different factors, to which the airports contribute by around 12%.

Primary Delays are the result of air traffic flows within the continent (e. g. Europe) and they affect the inter-continental traffic (e. g. Europe – U. S. A.), thus producing Reactionary Delays.

Increasing or optimizing the capacity of the airports can help reduce the overall delays significantly.

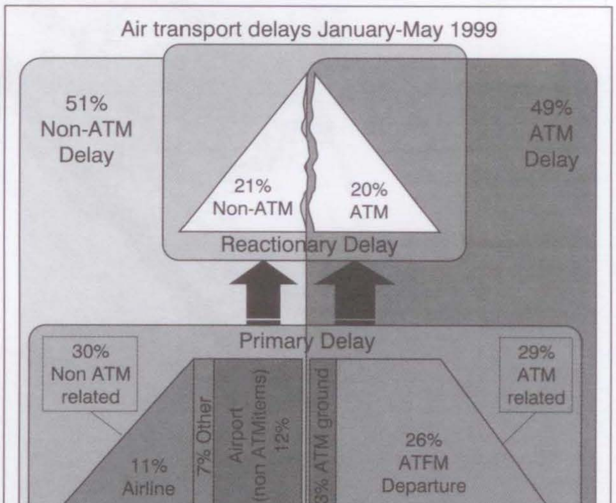

Figure 1 - Graphic presentation of the causes for delays1

But first of all, the present situation must be analysed.

2. CALCULATION OF THE RUNWAY CAPACITY

The traffic at Ljubljana Airport consists of IFR and VFR traffic. Only IFR traffic has been considered in the calculations. Although the VFR traffic presents a significant portion in the total amount of traffic, it is so flexible that in the end it only contributes to the overall capacity of the runway.

Ljubljana Airport is specific since there is no taxiway till the holding position of runway 31 [2]. Although the taxiway is being extended to the intersection F at the moment (Figure 2), the traffic can still not use it. For the purpose of calculations, it is therefore assumed that the aircraft of categories B and C, in case of take-off from runway 31 do not need to execute the backtrack on the runway, whereas aircraft of category A execute it if needed. The measured average time spent for that is 3 min.

Category A aircraft are jet aircraft, for example A-320, F-100, MD-80, CRJ and similar. Category B aircraft are turbo-prop aircraft like DHC-7/8, ATR-42/72, L-410, PC-9 and similar and category C aircraft are propeller aircraft like PARO, C-172/182, PASE and similar. All the above-mentioned types of aircraft are the most common types seen at Ljubljana Airport.

Aircraft generally land on runway 31. This is the only available instrumental runway for landing. Take-offs can be executed in the directions 31 or 13. Both directions are considered in the calculations. The composition of traffic is presented in Table 1.

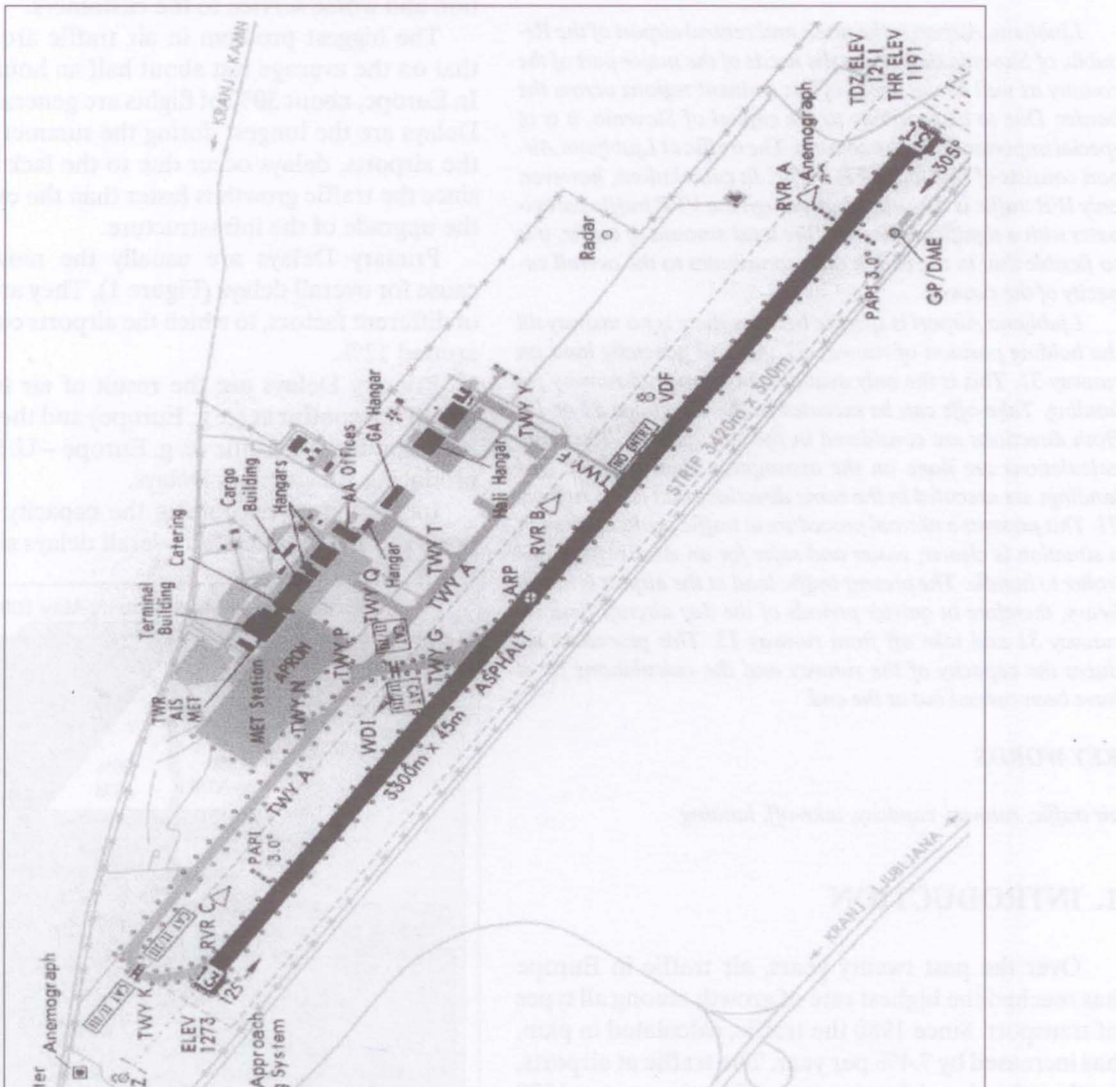

Figure 2 - Ljubljana Airport Layout

Table 1 – Composition of traffic at Ljubljana – Brnik Airport

Type of aircraft	Landing speed in Kts	Runway occupancy	Percentage of aircraft	
			Arriving	Departing
A	135	50	70	70
B	110	40	20	20
C	90	30	10	10

The majority of the operations are done by Adria Airways together with a few foreign carriers. Therefore, it can be assumed that the percentage of category A aircraft is the highest (around 70%). Around 20% of the operations are done by category B aircraft that are used by Solinair, Alpair, Tyrolean Air and Swiss. A smaller portion of that category represent also air force aircraft. The smallest part of operations (around 10%) is performed by category C aircraft, which are mainly training IFR flights. Since Ljubljana Airport is not an airport on which aircraft would remain parked for a longer period of time, it can be assumed that the percentage of arriving aircraft equals the percentage of departing aircraft and vice versa.

The basic calculations are done on the assumption that take-offs and landings are executed in the same direction, that is, on runway 31. This would be a normal procedure at traffic peaks because such situation is clearer, easier and safer for an Air Traffic Controller to handle. The present traffic load at the airport is not so heavy, therefore in quieter periods of the day aircraft land on runway 31 and take off on runway 13. This procedure reduces the capacity of the runway and the calculations for it are carried out at the end.

Table 2 shows the rules of separation of aircraft when taking-off and landing in the direction 31. The times in the matrix departures-departures are so long

Table 2 – Aircraft separation rules

Sequence of operations	Rules
Arrival - departure	Vacated runway
Departure - arrival	2Nm
Departure - departure	$\begin{array}{cc} & \text{Succeeding [s]} \\ & \begin{array}{ccc} A & B & C \end{array} \\ \text{Leading [s]} \begin{array}{c} A \\ B \\ C \end{array} & \begin{bmatrix} 240 & 240 & 240 \\ 240 & 180 & 120 \\ 240 & 180 & 180 \end{bmatrix} \end{array}$
Arrival – arrival	$\begin{array}{cc} & \text{Succeeding [Nm]} \\ & \begin{array}{ccc} A & B & C \end{array} \\ \text{Leading [Nm]} \begin{array}{c} A \\ B \\ C \end{array} & \begin{bmatrix} 5 & 5 & 5 \\ 7 & 5 & 5 \\ 9 & 7 & 5 \end{bmatrix} \end{array}$

because a minimum distance of 5 Nm must be maintained between two succeeding departures.

2.1. Calculations of the capacity for arrivals on runway 31

With the help of equations

$$\Delta T_{ij} = \frac{d_{ij} \cdot 3600}{v_i}$$

and

$$\Delta T_{ij} = \frac{d_{ij} \cdot 3600}{v_i} + l \cdot \left(\frac{1}{v_j} - \frac{1}{v_i} \right) \cdot 3600$$

a matrix of minimum separation times between arrivals M_{ij} is calculated [4].

$[M_{ij}]$:

$$\begin{array}{cc} & \text{Succeeding [s]} \\ & \begin{array}{ccc} A & B & C \end{array} \\ \text{Leading [s]} \begin{array}{c} A \\ B \\ C \end{array} & \begin{bmatrix} 134 & 134 & 134 \\ 251 & 164 & 164 \\ 380 & 306 & 200 \end{bmatrix} \end{array}$$

Where:

ΔT_{ij} – time between arrivals;

d_{ij} – minimum necessary distance between two succeeding aircraft;

l – distance of the arrival path;

v_i – speed of the leading aircraft;

v_j – speed of the succeeding aircraft;

Then a matrix of probabilities of sequences of operations P_{ij} is calculated, based upon the data from Table 1.

$[P_{ij}]$:

$$\begin{array}{cc} & \text{Succeeding} \\ & \begin{array}{ccc} A & B & C \end{array} \\ \text{Leading} \begin{array}{c} A \\ B \\ C \end{array} & \begin{bmatrix} 0.49 & 0.14 & 0.07 \\ 0.14 & 0.04 & 0.02 \\ 0.07 & 0.02 & 0.01 \end{bmatrix} \end{array}$$

Finally, with the help of equations

$$b_{ij} = q_v \cdot \sigma_0$$

and

$$b_{ij} = q_v \cdot \sigma_0 - d_{ij} \left(\frac{1}{v_j} - \frac{1}{v_i} \right),$$

a matrix of buffer times B_{ij} is calculated. Here, it is assumed that the standard deviation σ_0=20s and the probability of error is 10%, meaning that q_v =1.28.

$[B_{ij}]$:

$$\begin{array}{cc} & \text{Succeeding [s]} \\ & \begin{array}{ccc} A & B & C \end{array} \\ \text{Leading [s]} \begin{array}{c} A \\ B \\ C \end{array} & \begin{bmatrix} 26 & 26 & 26 \\ 0 & 26 & 26 \\ 0 & 0 & 26 \end{bmatrix} \end{array}$$

$[M_{ij}+B_{ij}]$:

$$\begin{array}{cc} & \text{Succeeding [s]} \\ & \begin{array}{ccc} A & B & C \end{array} \\ \text{Leading [s]} \begin{array}{c} A \\ B \\ C \end{array} & \begin{bmatrix} 160 & 160 & 160 \\ 251 & 190 & 190 \\ 380 & 306 & 226 \end{bmatrix} \end{array}$$

The expected time between arrivals is calculated with the help of the following equation:

$$E(\Delta T_{ij})=\Sigma[P_{ij}]\,[M_{ij}+B_{ij}]$$

and is $E(\Delta T_{ij})=194$s

Runway capacity for arrivals only is:

$$C_a=\frac{3600}{194}=19 \text{ oper/h}$$

2.2. Calculations of capacity for departures from runway 31

The expected time between departures is calculated with the help of the following equation:

$$E(t_d)=\Sigma[P_{ij}][t_d]$$

and is $E(t_d)=234$s

Runway capacity for departures only is:

$$C_d=\frac{3600}{234}=16 \text{ oper/h}$$

2.3. Calculations of the capacity for mixed operations on runway 31

In order to calculate the runway capacity for mixed operations, the expected time between the departures must be equal to or greater than the expected time between the arrivals that is calculated in the following way:

$$E(\Delta T_{ij})\geq E(R_i)+E\left(\frac{\delta_d}{v_j}\right)+(n_d-1)\cdot E(t_d)$$

$$E(R_i)50\cdot 0.7+40\cdot 0.2+30\cdot 0.1=46 \text{ s}$$

$$E\left(\frac{\delta_d}{v_j}\right)=\left[\frac{0.7\cdot 2}{135}+\frac{0.2\cdot 2}{110}+\frac{0.1\cdot 2}{90}\right]\cdot 3600=59 \text{ s}$$

$$E(B_{ij})=26\cdot 0.77+0\cdot 0.23=20 \text{ s}$$

$$E(t_d)=234 \text{ s}$$

It means that:

$$E(\Delta T_{ij})\geq 46+59+20+234(n_d-1)\geq 125+234(n_d-1)$$

In order to release one departure, a time gap of 125s is needed between two arrivals. To release two departures, a time gap of 359s is needed between two arrivals. To release three departures, a time gap of 593s is needed between two arrivals, etc.

This only holds true if the aircraft do not perform a backtrack on the runway, which in our case is not true for category A aircraft.

By observing the matrix for arrivals, it can be concluded that the probability to release one departure between two arrivals equals 30%, the probability to release two departures between two arrivals equals 7% and the probability to release three departures between two arrivals equals 0%. This means that no more than two departures can be released between two arrivals if the minimum separation between arrivals is applied.

Runway capacity for mixed operations, arrivals and departures on runway 31, is:

$$C_m=\frac{3600}{234}\cdot(1+0.3\cdot 1+0.07\cdot 2)=23 \text{ oper/h}$$

2.4. Calculation of the ultimate capacity for arrivals and departures on runway 31

Based upon the observations of the traffic at Ljubljana Airport, it can be assumed that in the period of one hour for about 20 min the aircraft have been only departing, for another 20 min aircraft have been only arriving and during the last 20 min mixed operations have been performed. The **ultimate runway capacity**, based upon the above-mentioned assumptions, is calculated in the following way:

$$C_r=(0.33\cdot C_a+0.33\cdot C_m+0.33\cdot C_d)=$$
$$=(0.33\cdot 19+0.33\cdot 23+0.33\cdot 16)=20 \text{ oper/h}$$

2.5. Calculation of the capacity for departures from runway 13 and arrivals on runway 31

For operations, where take-offs and landings are performed head to head, the above-described model cannot be entirely used. Minimum separations and the philosophy of calculations change considerably. The runway capacity for arrivals on runway 31 only remains the same, that is, 19 operations per hour. The runway capacity for departures only is even increased since category A aircraft do not need to execute a backtrack on the runway. The calculation of the runway capacity for mixed operations is an item for itself.

2.5.1. Calculation of capacity for departures from runway 13

For calculation of the runway capacity for departures from runway 13, a new matrix of separation times between departures will be used. The matrix is modified due to the fact that category A aircraft do not need to execute a backtrack on the runway. The new matrix [t_d] is the following:

[t_d]:

$$\begin{array}{cc} & \text{Succeeding [s]} \\ & \begin{array}{ccc} A & B & C \end{array} \\ \text{Leading } [s] \begin{array}{c} A \\ B \\ C \end{array} & \begin{bmatrix} 120 & 90 & 60 \\ 240 & 180 & 120 \\ 240 & 180 & 180 \end{bmatrix} \end{array}$$

The expected time between departures is calculated with the help of the following equation:

$$E(t_d) = \Sigma[P_{ij}][t_d]$$

and $E(t_d)=141$s

Runway capacity for departures only is:

$$C_d = \frac{3600}{141} = 26 \text{ oper/h}$$

2.5.2. Calculation of the capacity for mixed operations 13 - 31

If departures are released from runway 13, then the minimum separation between the departure and the arrival in Table 2 is not 2 Nm any more but significantly more, depending on the speed of the aircraft. The departing aircraft must take off, overfly the whole length of the runway, climb towards MG (locator) and move away from the arrival path by at least 5Nm before the arriving aircraft can intercept the arrival path and start the approach. The minimum possible separation between the arrivals cannot be applied any more and the arrivals do not have the ultimate priority any longer.

Departing aircraft must overfly the whole length of the runway (1.8 Nm), the path from the threshold of the runway to MG (4.2 Nm) and move away from the approach path by at least 5 Nm. The overall length of the path of the departing aircraft is therefore 11 Nm. The time needed to overfly that distance is the following:

- Category A 200 s;
- Category B 270 s;
- Category C 400 s.
- The arriving aircraft must overfly the whole distance of the approach path (10.5 Nm) and vacate the runway. The time needed to do this is the following:
- Category A 330 s;
- Category B 380 s;
- Category C 450 s.

The matrix of the departure - arrival [t_{da}] cycle is the following:

[t_{da}]:

$$\begin{array}{cc} & \text{Arrival [s]} \\ & \begin{array}{ccc} A & B & C \end{array} \\ \text{Departure } [s] \begin{array}{c} A \\ B \\ C \end{array} & \begin{bmatrix} 530 & 580 & 650 \\ 600 & 650 & 720 \\ 730 & 780 & 850 \end{bmatrix} \end{array}$$

The expected time for the departure – arrival cycle is calculated with the help of the following equation:

$$E(t_{da}) = \Sigma[P_{ij}][t_{da}]$$

and $E(t_{da}) = 586$ s

Runway capacity for mixed operations is:

$$C_m = \frac{3600}{586} \cdot 2 = 13 \text{ oper/h}$$

2.5.3. Calculation of the ultimate capacity for arrivals on runway 31 and departures from runway 13

Here it can also be assumed that in the period of one hour for about 20 min aircraft are only departing, for another 20 min aircraft are only arriving and during the last 20 min mixed operations are performed. Based upon the above-mentioned assumptions, the **ultimate runway capacity** is calculated in the following way:

$$\begin{aligned} C_r &= (0.33 \cdot C_a + 0.33 \cdot C_m + 0.33 \cdot C_d) = \\ &= (0.33 \cdot 19 + 0.33 \cdot 13 + 0.33 \cdot 26) = 20 \text{ oper/h} \end{aligned}$$

3. CONCLUSION

This paper presents the Ljubljana – Brnik Airport and different calculations of the runway capacity for all the possible combinations that exist in reality.

By observing the results, it can be concluded that the capacity for mixed operations drops significantly if departures and arrivals are released head to head because the departing aircraft needs a lot of time to move away safely from the arriving aircraft. The handicap is also the high terrain close to the threshold. The departing aircraft therefore cannot turn away from the runway heading before crossing MG. In IMC conditions there would be high risk of collision with the terrain.

It is also obvious that the runway capacity increases a lot if aircraft depart from runway 13 since category A aircraft do not need to execute a backtrack on the runway. This contributes considerably to the fact that the runway capacity remains the same in cases when departures and arrivals are released head to head on the assumption that during 1/3 of the time aircraft are only departing, 1/3 of the time the aircraft are only arriving and during1/3 of the time mixed operations are performed.

Presently, the number of operations at Ljubljana – Brnik Airport is relatively low, therefore, the runway capacity is not a major obstruction. However, in case of traffic increase, the orientation of the traffic flow can start influencing the capacity of the airport as well as the safety of operations.

ANDREJ GREBENŠEK, B. Sc.
Ministarstvo za promet
Uprava Republike Slovenije za civilno letalstvo
Kotnikova 19a, 1000 Ljubljana, Republika Slovenija
e-mail: andrej.grebensek@caa-rs.si
STANISLAV PAVLIN, D. Sc.
Sveučilište u Zagrebu
Fakultet prometnih znanosti
Vukelićeva 4, 10000 Zagreb, Republika Hrvatska

POVZETEK

Letališče Ljubljana je glavno in osrednje letališče Republike Slovenije, ki z opravljanjem letaliških in komercialnih storitev pokriva potrebe pretežnega dela države in obmejnih območij sosednjih držav, zaradi bližine glavnega mesta države, pa ima še poseben pomen in vlogo za državo. Promet na letališču Ljubljana – Brnik zajema IFR in VFR promet. V izračunu je obravnavan samo IFR promet. Kljub temu, da je VFR prometa na letališču veliko, pa je le-ta prilagodljiv do te mere, da se kapaciteta vzletno – pristajalne steze z njegovim obravnavanjem samo poveča.

Ljubljansko letališče je specifično, saj nima izgrajene steze za voženje vse do praga steze 31. Letala načeloma pristajajo v smeri steze 31, kjer je tudi edini možni instrumentni prihod. Vzletanje letal pa je lahko v smeri steze 31 ali 13. V izračunu sta obravnavana oba primera. Osnovni izračun je izveden ob predpostavki, da se prileti in odleti letal izvajajo v isti smeri, to je v smeri 31. To bi tudi bil normalni način dela ob prometnih konicah, saj je bolj pregleden in za kontrolorja letenja lažji ter varnejši. Ker pa je trenutna obremenjenost letališča relativno majhna, se v času manjše intenzivnosti prometa delo izvaja tako, da letala pristajajo v smeri 31 in vzletajo v smeri 13. Tak način dela zmanjša kapaciteto vzletno pristajalne steze in je obravnavan na koncu.

KLJUČNE BESEDE

zračni promet, vzletno-pristajalna steza, kapaciteta, vzletanje, pristajanje

LITERATURE

[1] Internet: http://europa.eu.int/comm/transport/themes/air//english/single_eur_sky_en.html;

[2] Ministarstvo za promet in zveze, Uprava republike Slovenije za civilno letalstvo: AIP – Aeronautical Information Publication - Zbornik zrakoplovnih informacij;

[3] Internet: http://www.lju-airport.si/default.htm;

[4] **Robert Horonjeff – Francis X. McKelvey:** *Planning and Design of Airports*, fourth edition1993, McGraw – Hill, Inc.